



City Research Online

City St George's, University of London

Citation: Tamanna, N. (2019). Modelling of residual stresses of the laser cladding process. (Unpublished Doctoral thesis, City, University of London)

This is the accepted version of the paper.

This version of the publication may differ from the final published version. To cite this item please consult the publisher's version.

Permanent repository link: <https://openaccess.city.ac.uk/id/eprint/24395/>

Copyright and Reuse: Copyright and Moral Rights remain with the author(s) and/or copyright holders. Copies of full items can be used for personal research or study, educational, or not-for-profit purposes without prior permission or charge, unless otherwise indicated, provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way. For full details of reuse please refer to [City Research Online policy](#).

Modelling of residual stresses of the Laser Cladding process

By

Nusrat Tamanna

Thesis submitted for the degree of
Doctor of Philosophy



Department of Mechanical Engineering and Aeronautics,

City, University of London, United Kingdom

Supervisor: Dr. Sumsun Naher

2019

Declaration

I sincerely declare that I am the sole author of this dissertation and the work in this dissertation was carried out in accordance with the requirements of the regulations by City, University of London, UK. All intellectual contents in this document are original and entirely my effort. The use of published literatures, textbooks and theses which have copyright are cited and, title of works and authors have been carefully acknowledged. This original work has not been submitted either in whole or in part for consideration of any academic or professional degree to any other University.

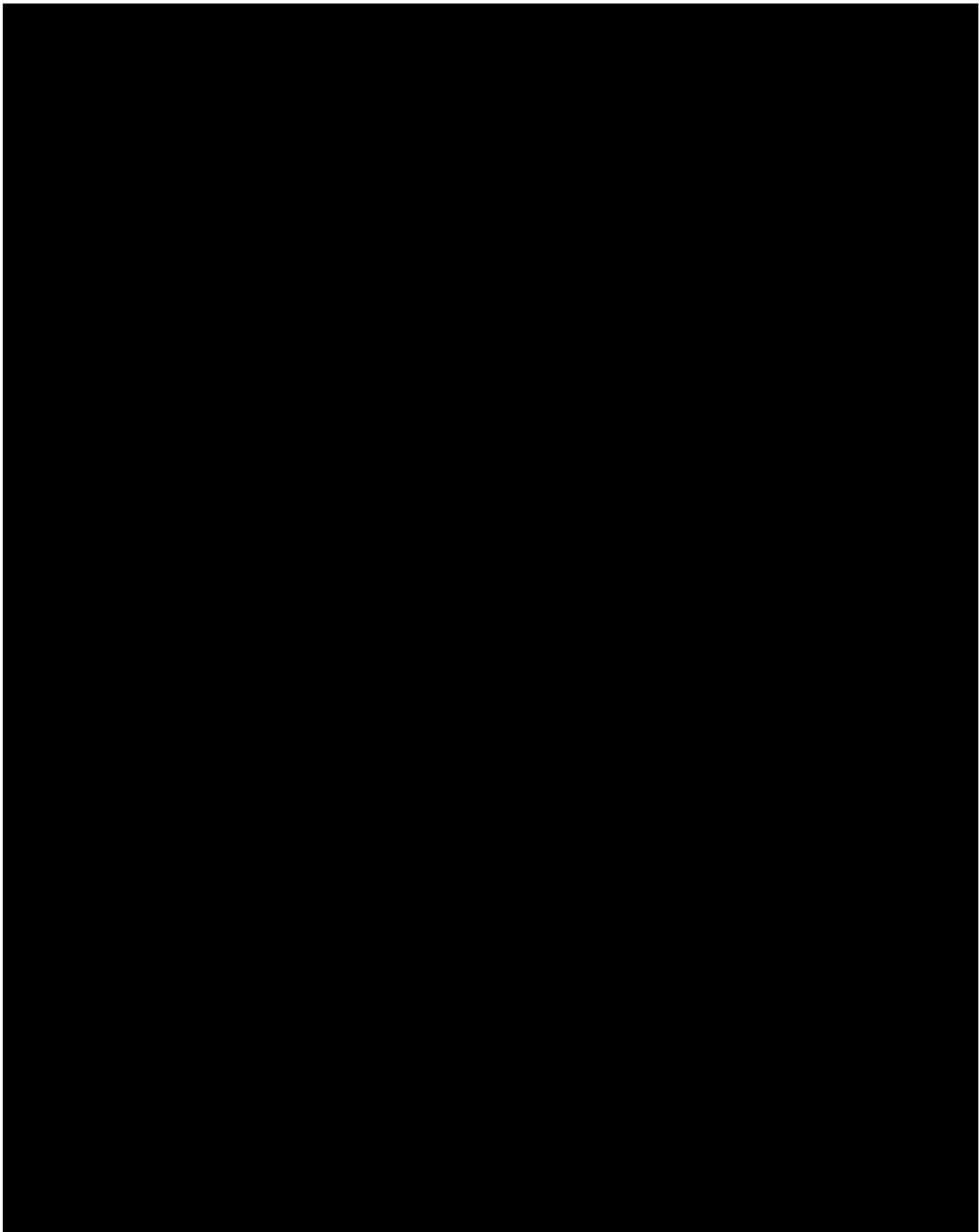
.....

Nusrat Tamanna

July, 2019

Dedicated to
The Almighty Allah and
My parents 

Acknowledgement



List of publications

Journal papers

1. **Tamanna Nusrat**, Crouch Roger and Naher Sumsun; Progress on Numerical Simulation in the Laser Cladding Process; Laser and Optics in Engineering, 122, 2019, 151-163. <https://doi.org/10.1016/j.optlaseng.2019.05.026>
2. **Tamanna Nusrat**, Crouch Roger, Kabir Israt and Naher Sumsun; An analytical model to predict and minimize the residual stress of laser cladding process; Applied Physics A; 124; 202; 2018;1-5. <https://doi.org/10.1007/s00339-018-1585-6>
3. Kabir Israt, Yin Danqing, **Tamanna Nusrat** and Naher Sumsun; Thermomechanical modelling of laser surface glazing for H13 tool steel; Applied Physics A; 124; 260; 2018;1-9. <https://doi.org/10.1007/s00339-018-1671-9>
4. **Tamanna Nusrat**, Kabir Israt and Naher Sumsun; A numerical investigation of similar and dissimilar clad materials on H13 steel substrate in the Laser Cladding process; Advances in Materials and Processing Technologies, 2019, <https://doi.org/10.1080/2374068X.2019.1660558>.
5. **Tamanna Nusrat** and Naher Sumsun; Effect of material properties on the formation of residual stresses in the Laser Cladding process” (manuscript in preparation).

Conference papers

1. **Tamanna Nusrat**, Islam Rukon, Qaban Abdullah and Naher Sumsun; A numerical investigation of similar and dissimilar clad materials in the Laser Cladding process, 21st International Conference on Advances in Materials & Processing Technologies: AMPT 2018, 4-7 September, 2018, Dublin, Ireland.
2. **Tamanna Nusrat**, Crouch Roger and Naher Sumsun, Progress on Numerical Simulation in the Laser Cladding Process; 26th International Conference on Composites or Nano Engineering (ICCE-26), July 15-21, 2018, Paris, France.
3. **Tamanna Nusrat**, Crouch Roger, Kabir Israt and Naher Sumsun, An Analytical Model to Calculate and Minimize the Residual Stress of Laser Cladding Process, COLA 2017: International Conference on Laser Ablation, 3-8 September, 2017, Marseille, France.
4. **Tamanna Nusrat**, Crouch Roger and Naher Sumsun, A One-dimensional Analysis of the Distribution of Temperature, Stress and Strain in the co-axial Laser Cladding Process, 20th International ESAFORM Conference on Material Forming, April 24-28, 2017, Dublin, Ireland.

Abstract

The focus of this work is to predict residual stresses and find the key controlling factors in formation of residual stresses in the Laser Cladding process. Three types of models (conceptual, analytical and numerical) have been developed to understand the process and predict residual stresses. The conceptual model describes the simplified relation of temperature, stress and strain with time schematically using the established theoretical knowledge of generation of strain and stress after thermal treatment. A one dimensional analytical model was adopted to predict residual stresses in dissimilar clad and substrate materials. H13 steel and Ti6Al4V were used as substrate material. Four cladding materials (Al_2O_3 , TiC, TiO_2 and ZrO_2) were used on the H13 steel substrate and a range of preheating temperature of the substrate, from 300 K to 1200 K, was investigated. The minimum residual stress was found for Al_2O_3 clad on the H13 steel substrate. For Ti6Al4V substrate, six cladding materials (Al_2O_3 , TiC, TiO_2 , ZrO_2 , SiC and TiN) were used and, 300 K to 1000 K was the range of preheating temperature of the substrate. TiN cladding material generated the maximum tensile residual stress. Below 1000 K, SiC formed minimum residual stresses on the Ti6Al4V substrate. In both cases, the increment of preheating temperature of substrate decreased the residual stress.

2D and 3D thermo-mechanical models were developed to predict temperature distribution and residual stress distribution using commercial software (ANSYS'18). In 2D numerical model, as a substrate material H13 steel was used and H13 steel, Al_2O_3 and TiC were used as clad materials. Tensile residual stresses were observed in the clad, at interface of the clad and the substrate and in the substrate near the interface in all samples. It was found that Al_2O_3 coating on H13 steel produced lower residual stress (1220 MPa) in the clad than TiC coating on H13 steel (1359 MPa). The proposed analysis offers to select the combination of clad and substrate materials having minimum residual stresses in this process.

A 3D thermo-mechanical model of deposition of Ti6Al4V clad on the Ti6Al4V substrate material was developed. This model was verified with an established model in order to establish the accuracy of mesh and the applied boundary conditions. Temperature history of this model offers the knowledge about the peak temperature at the interface (3201 K), shape and depth of melt pool (0.5 mm) and HAZ (0.23 mm), the formation time of melt pool, heating rate (2.45×10^4 K/s), cooling rate (1.1×10^4 K/s) and microstructure in the heat treated area. The residual stress distribution shows maximum tensile stress was 108 MPa which is far below the yield strength (1061 MPa) of Ti6Al4V material.

Sequentially, three cladding materials (Al_2O_3 -1, Al_2O_3 -2 and TiC) were deposited on the surface of the Ti6Al4V substrate using similar model. The peak temperature at the interface for Al_2O_3 -1/Ti6Al4V and TiC/Ti6Al4V samples are 3101 K and 3911 K respectively. The maximum predicted equivalent stress (SEQV) in TiC/Ti6Al4V sample (274 MPa) was higher than Al_2O_3 -1/Ti6Al4V sample (205 MPa). Furthermore, Al_2O_3 -2 (α -alumina) generated higher tensile residual stresses than Al_2O_3 -1 (the refractory alumina) on the same substrate due to temperature dependant properties, Al_2O_3 -2/Ti6Al4V sample.

Contents

Declaration	i
Acknowledgement	iii
List of publications	iv
Journal papers	iv
Abstract	v
Nomenclature	ix
List of figures	xi
List of tables.....	xv
1 Introduction.....	1
1.1 Research challenge and aim of the research.....	1
1.2 Thesis outline.....	3
1.3 Contribution to the Knowledge	4
2 Literature review	6
2.1 Powder flow dynamics	10
2.1.1 Modelling of powder flow characteristics	12
2.1.2 Powder-nozzle interaction zone.....	13
2.1.3 Powder-laser interaction zone	14
2.1.4 Powder-substrate interaction zone	15
2.1.5 Experimental validation.....	18
2.2 Melt pool	19
2.2.1 Heat transfer in melt pool.....	19
2.2.2 Melt pool geometry and shape.....	24
2.2.3 Fluid flow in melt pool	24
2.2.4 Experimental validation.....	30
2.3 Clad properties.....	31

2.3.1	Modelling of clad properties.....	31
2.3.2	Experimental validation.....	35
2.4	Materials	37
2.5	The relevance of laser cladding processes in additive manufacturing	43
2.6	Research gap and future outlook	47
3	Conceptual model.....	50
3.1	Model set-up	50
3.2	Results and discussion	52
3.3	Conclusion	59
4	The analytical model.....	60
4.1	Model set-up	60
4.2	Results and discussion	63
4.2.1	H13 steel substrate.....	63
4.2.2	Ti6Al4V substrate	69
4.3	Conclusion	74
5	2D FE model for single step heat source	75
5.1	Model set up	75
5.1.1	Geometry and mesh	75
5.1.2	Materials and properties	77
5.1.3	Laser parameters.....	78
5.2	Results and discussion	79
5.2.1	Thermal analysis.....	79
5.2.2	Residual stresses analysis	81
5.3	Conclusion	84
6	3D moving heat source model of Ti6Al4V (substrate)/Ti6Al4V (clad) sample.....	86
6.1	Model set up	86
6.1.1	3D Geometry and mesh.....	86
6.1.2	Material properties	89

6.2	Verification of the model.....	92
6.3	Results and discussion	95
6.3.1	Optimization of process parameters for 3D model.....	95
6.3.2	Temperature distribution.....	97
6.3.3	Residual stress distribution.....	104
6.4	Conclusion	106
7	3D model of Al₂O₃/Ti6Al4V and TiC/Ti6Al4V samples	108
7.1	Model set up	108
7.1.1	3D geometry and mesh	108
7.1.2	Materials properties	110
7.2	Laser parameters.....	114
7.3	Results and discussion	115
7.3.1	Optimization of process parameters	115
7.3.2	Temperature distribution.....	115
7.3.3	Residual stress distribution.....	119
7.3.4	Effect of temperature dependant material properties of Al ₂ O ₃	123
7.4	Conclusion	127
8	Summary and future work.....	128
8.1	Summary.....	128
8.2	Future work	132
	References	134
	Appendices	i
	Appendix A	i
	Appendix B	iii
	Appendix C	v

Nomenclature

a	It is a variable which takes the value 1 if T is melting temperature or 0 if T is different than melting point
A_p	The area of particle (m^2)
C_p	The specific heat (J/kg.K)
C_D	The drag coefficient
∂T	The particle temperature variation in the time ∂t (K)
e	The dimensionality of growth of phases
f	The external force acting on gas
f'	The volume fraction of the new phase
f''	Instantaneous volume fraction of the new phase
f'''	The volume fraction of the new phase for non-isothermal phase transformation
g	Gravity force (m/s^2)
H	The heat convection coefficient ($\text{W/m}^2.\text{K}$)
I_{dir}	The energy incident on the particle coming from the direct beam (J)
I_{ref}	The incident energy coming from substrate reflection (J)
k	Thermal conductivity (W/m.K)
K	A temperature dependent crystallization rate
L_f	The latent heat of fusion (J/kg)
m_p	The mass of a particle (kg)
M_s	The martensitic transformation temperature
m	A coefficient dependent on the temperature, composition of parent phase, and grain size
N	Permeability coefficient
n	A coefficient dependent on the type of phase transformation and grain growth
P	Laser power
p	The pressure of gas/liquid (Pa)
Q_{laser}	The heat flux from laser heat source (W/m^2)
r	The radial distance from the centre of laser heat source (m)
r_p	The particle radius (μm)
R	Radius of the laser beam (μm)

S_x, S_y, S_z	Source of momentum per unit volume per unit time in X, Y and Z direction
T	The temperature of the particle (K)
T_β	The beta transus temperature (K)
T_∞	The temperature of the surrounding gas (K)
t	The phase transformation time duration (s)
t_o	Initial time of phase transformation (s)
t_e	End time of phase transformation (s)
U	Velocity of laser head (m/s)
u, v, w	Velocity component in X, Y and Z (m/s)
u_s	Tangential velocity at free surface (m/s)
v_s	Normal velocity at free surface (m/s)
w_s	Tangential velocity at free surface (m/s)
v_p	The velocity of particle (m/s)
V	Velocity vector (m/s)
U	Instantaneous velocity of gas field (m/s)
U, V and W	Velocity component at X, Y and Z direction in turbulent flow
X, Y, Z	Cartesian coordinate (m)
∇	Vector differential operator/ grad operator
LFD	Laser focus distance
SOD	Stand of distance
BOE	Bounce off effect
Greek symbol	
E	The particle emissivity
$\varepsilon^{el}, \varepsilon^{pl}, \varepsilon^{th}, \varepsilon^{\nabla V}, \varepsilon^{Trp}$	Elastic, plastic, thermal, volumetric and phase transformation strain respectively
H	The absorptivity of laser power
η_p	The absorption coefficient of particle
M	The molecular viscosity (kg/m.s)
μ_l	The dynamic viscosity (kg/m.s)
ρ_l	Density of liquid phase (kg/m ³)
ρ	The density of gas/clad/substrate material (kg/m ³)
ρ_p	The density of the particle (kg/m ³)
Σ	The Stefan-Boltzman constant
τ_t	Pulse duration (s)

List of figures

Fig. 2.1 Schematic diagrams of feeding system (a) preplaced powder system, (b) co-axial powder system, (c) off-axis powder system and (d) wire feeding system.....	7
Fig. 2.2 (a) A schematic diagram of the coaxial Laser Cladding process, (b) micrograph, presenting deposited clad, HAZ and substrate area [10].	8
Fig. 2.3 Schematic diagram of several interaction zones along the laser beam to substrate. The interactions can be divided into three zones such as (a) powder-nozzle [42,47], (b) powder-laser [30,47,49,51] and (c) powder-substrate [30]. LFD = laser focus distance, SOD = stand of distance, BOE = bounce off effect.	12
Fig. 2.4 Three dimensional temperature distribution of (a) preplaced [73] and (b) coaxial powder system [71] using FEM.	23
Fig. 2.5 Predicted residual stress distribution in longitudinal direction using FEM [10].....	35
Fig. 2.6 The categories of additive manufacturing technology based on materials and machine technology [148,149].....	43
Fig. 2.7 Available models of the Laser Cladding process can be applied for additive manufacturing.....	46
Fig. 3.1 A schematic diagram of (a) the clad and the substrate material and (b) the direction of the normal stresses (σ_{xx} , σ_{yy}) and strains (ϵ_x , ϵ_y) in a 2D element.	51
Fig. 3.2 The transient heating and cooling cycle during the thermal process.....	53
Fig. 3.3 The one-dimensional representation of the change of length with time during heating and cooling process.	55
Fig. 3.4 Schematic diagrams of strain-time of the Laser Cladding process.....	57
Fig. 3.5 Schematic diagrams of stress-time of the Laser Cladding process.....	58
Fig. 4.1 The geometry of residual stress model based on thermos-elastic mechanics [164].....	62
Fig. 4.2 Distribution of the normalized residual stress with preheating temperature of H13 steel substrate for four cladding materials.....	63

Fig. 4.3 The normalized residual stress (a) at 300 K and (b) at 1200 K preheating temperature of H13 steel substrate for four cladding materials.	66
Fig. 4.4 Mismatch of thermal strain between cladding materials and the H13 steel substrate (a) at 300 K and (b) at 1200 K preheating temperature of the substrate.	67
Fig. 4.5 Product of mismatch of thermal strain and Young's modulus (a) at 300 K and (b) at 1200 K preheating temperature of H13 steel substrate for four cladding materials.	68
Fig. 4.6 Distribution of the normalized residual stresses with preheating temperature of Ti6Al4V substrate for six cladding materials.	69
Fig. 4.7 The normalized residual stress (a) at 300 K and (b) at 1000 K preheating temperature of Ti6Al4V substrate for four cladding materials.	71
Fig. 4.8 Mismatch of thermal strain between cladding materials and Ti6Al4V substrate (a) at 300 K and (b) at 1000 K preheating temperature of the substrate.	72
Fig. 4.9 Product of mismatch of thermal strain and Young's modulus (a) at 300 K and (b) at 1000 K preheating temperature of Ti6Al4V substrate for six cladding materials.	73
Fig. 5.1 The 2D model geometry (mm) and mesh.	76
Fig. 5.2 Mesh convergence of 2D finite element model.	77
Fig. 5.3 The 2D temperature distribution (K) at 0.053 s. Power = 350 W, beam diameter = 0.74 mm and scanning speed = 14.8 mm/s.	80
Fig. 5.4 Temperature vs time distribution of H13/H13, Al ₂ O ₃ /H13 and TiC/H13 cladding samples.	81
Fig. 5.5 (a) Geometry and mesh, residual stresses distribution at CD line in X and Y direction are given for (b) H13/H13, (c) Al ₂ O ₃ /H13 and (d) TiC/H13 cladding systems.	83
Fig. 5.6 Residual stresses (shear stresses) distribution at CD line in X and Y direction are given for (b) H13/H13, (c) Al ₂ O ₃ /H13 and (d) TiC/H13 cladding systems.	84
Fig. 6.1 The geometry of 3D model. All dimensions are in mm.	87
Fig. 6.2 The meshing of the 3D symmetry model.	87

Fig. 6.3 Mesh convergence of 3D of model.....	88
Fig. 6.4 Temperature dependent thermal properties (a) thermal conductivity and (b) specific heat capacity.	90
Fig. 6.5 Temperature dependent mechanical properties (a) Young's modulus and thermal expansion coefficient and (b) Yeild stress and tangent modulus of Ti6Al4V.....	91
Fig. 6.6 The predicted temperature distribution (a) developed model by Hao et al. [71] and (b) developed model by author.....	93
Fig. 6.7 The melt pool depth of (a) modelling and experimental results by Hao et al. and (b) current work by author.	94
Fig. 6.8 The temperature distribution of the 3D model at 1.339 s. Power = 600 W, beam diameter = 0.7 mm and scanning speed = 700 mm/s.....	97
Fig. 6.9 (a) The temperature distribution of the 3D model at 1.339 s. Power = 600 W, beam diameter = 0.7 mm and scanning speed = 700 mm/s, (b) selected top view of melt pool, (c) section view BB' and (d) view at symmetry plane.	98
Fig. 6.10 The temperature distribution from the clad surface to the bottom of the substrate.	99
Fig. 6.11 (a) Monitoring position of temperature distribution, (b) temperature distribution and (c) heating and cooling rate at three different positions.....	101
Fig. 6.12 (a) Temperature distribution at five positions along the depth and (b) heating and cooling rate at these positions.....	103
Fig. 6.13 The residual stresses distribution at the path MN, from the top of the clad surface to the bottom of the substrate.	105
Fig. 6.14 The residual stress distribution at the path OP, from the symmetry plane to the right end of the substrate.	105
Fig. 7.1 The geometry of 3D model. All dimensions are in mm.	109
Fig. 7.2 The meshing of the 3D symmetry model.....	110
Fig. 7.3 Temperature dependent thermal properties of Al ₂ O ₃ -2 (a) thermal conductivity and (b) specific heat capacity.....	112
Fig. 7.4 Temperature dependent mechanical properties of of Al ₂ O ₃ -2 (a) thermal expansion coefficient and (b) Young's modulus and poission ratio.....	113

Fig. 7.5 The transient temperature distribution of Al_2O_3 -1/Ti6Al4V and TiC/Ti6Al4V samples	116
Fig. 7.6 Heating and cooling cycles of Al_2O_3 -1/Ti6Al4V and TiC/Ti6Al4V samples.	118
Fig. 7.7 The temperature distribution from the clad surface to the bottom of the substrate of Al_2O_3 -1/Ti6Al4V and TiC/Ti6Al4V samples.	118
Fig. 7.8 The residual stresses distribution of Al_2O_3 -1/Ti6Al4V along the path MN.	119
Fig. 7.9 The residual stresses distribution of Al_2O_3 -1/Ti6Al4V along the path OP.	120
Fig. 7.10 The residual stresses distribution of TiC/Ti6Al4V along the path MN...	121
Fig. 7.11 The residual stresses distribution of TiC/Ti6Al4V along the path OP. ...	122
Fig. 7.12 Temperature distribution of Al_2O_3 -1/Ti6Al4V and Al_2O_3 -2/Ti6Al4V samples.	123
Fig. 7.13 The residual stresses distribution of Al_2O_3 -1/Ti6Al4V and Al_2O_3 -2/Ti6Al4V samples along the path MN.....	125
Fig. 7.14 The residual stresses distribution of Al_2O_3 -1/Ti6Al4V and Al_2O_3 -2/Ti6Al4V samples along the path OP.	126

List of tables

Table 2.1 The chronological development of numerical models on powder flow dynamics for co-axial powder type.....	16
Table 2.2 Chronological development of thermal model in melt pool.....	27
Table 2.3 The applied materials in the experimental work.	38
Table 4.1 The material properties of H13 steel and cladding materials.....	61
Table 4.2 The material properties of Ti6Al4V and cladding materials.	61
Table 5.1 Thermo-mechanical properties of H13 steel [115], Al ₂ O ₃ [174] and TiC [167] materials.....	78
Table 5.2 Laser process parameters for H13/H13 [115], Al ₂ O ₃ /H13 [175] and TiC/H13 [175] cladding samples. Note that in all cases the substrate is H13 tool steel.....	79
Table 6.1 The chemical composition of Ti6Al4V material [71].....	89
Table 6.2 Comparison of predicted results between the model of Hao et al. [71] and the current model.....	94
Table 6.3 Optimisation of process parameters (laser power and beam radius). ...	96
Table 7.1 Thermo-mechanical properties of Al ₂ O ₃ -1 [174] and TiC [185] materials.	111
Table 7.2 Laser parameters for deposition of Al ₂ O ₃ -1/Ti6Al4V and TiC/Ti6Al4V samples.	114
Table 7.3 Optimisation of laser power for Al ₂ O ₃ -1/Ti6Al4V and TiC/Ti6Al4V samples.	115

1 Introduction

With the rapid and fast diversification of laser applications, the development of surface treatments for the metallic parts is technologically improved in aeronautical, automotive, agricultural, manufacturing of space transportation infrastructure and remanufacturing industries [1–4]. Laser Cladding (LC) is one of the significant applications of laser technology. In the LC process, a laser heat source is utilized to deposit a thin layer (0.05-2 mm) of metal/ceramic, known as clad, on a solid substrate. This process offers high process accuracy, low heat input, excellent metallurgical bonding and lower percentage of porosity over other conventional thermal processes such as arc welding, flame spraying and plasma spraying [5]. Additionally, the diversification of material processing such as metallic/ceramic coatings, repairing, prototyping and rapid tooling made this process more popular in recent years [1–4,6]. Wear, corrosion and oxidation resistance coatings of turbine blades, feed screws, seals, high compression valves, engine valve seats and boiler tubes are commercially in production. The popular repairing and tooling applications of this process are forging dies, extruders, mould, turbine engine vanes and cutting tools. Recently, Technavio has published that the Laser Cladding in the tooling segment increases the life of the product over 70% [7]. Thus, projected the market of the Laser Cladding to reach ~\$1 billion by 2021. Though this is established as one of the best thermal coating processes, the generation of the tensile residual stresses in the thermally treated area is one of the main problems that need to be addressed [8,9].

1.1 Research challenge and aim of the research

High speed deposition of different materials, fast heating and cooling introduce the mismatch of strain between the clad and the substrate material. The generated

strain results in residual stresses in the clad and the substrate. Mainly, tensile residual stresses were found in the clad, which causes dimensional inaccuracy, cracking, distortion and failure of components during the process and in use [10–12]. Moreover, tensile residual stress on the surface of the mechanical component is the main reason of drastic reduction of fatigue strength and stress corrosion cracking [13]. However, the reasons of formation of residual stresses and their nature, how residual stresses are forming in the system and how to minimize the residual stresses are not clearly defined yet. Thus, the aim of this work is to predict residual stresses, find controlling parameters of the formation of residual stresses and analyse different material properties which could minimise residual stresses in the laser cladding process. In order to understand and predict residual stresses in LC process, the overall objectives are to

1. develop a conceptual model to understand the temperature distribution and development of the residual stress distribution in the Laser Cladding process from established theory and previous experimental results.
2. predict residual stresses for dissimilar clad/substrate materials using an analytical model and find the key reasons behind the formation of residual stresses.
3. develop 2D and 3D numerical models for similar and dissimilar clad/substrate materials using Multiphysics modelling platform (ANSYS'18) and predict the temperature distribution and residual stresses.
4. optimise the process parameters and materials
 - a) laser process parameters such as laser power and beam radius
 - b) different substrate and cladding materials and their properties

1.2 Thesis outline

This thesis comprises eight chapters including the current chapter and future work. Appendices have been added at the end of this thesis. A brief summary of these chapters are described below

Chapter 1 - This chapter introduces the readers to the importance of the Laser Cladding process, the research question, aim of the research and contribution to knowledge.

Chapter 2 - This chapter reviews the literature and necessary background theory of the Laser Cladding process. A brief history of the Laser Cladding process, feeding systems, the progress of numerical simulations spanning over three distinct stages (powder flow dynamics, melt pool and clad properties), the relevance of laser cladding process with additive manufacturing have been presented.

Chapter 3 - This chapter outlines a physical model of the clad and the substrate to describe the simplified relation of temperature, strain and stress with time schematically using the established theoretical knowledge of generation of strain and stress after thermal treatment.

Chapter 4 - This chapter focuses on the development of a one dimensional analytical model to predict residual stresses in dissimilar clad and substrate materials. The detail derivation of the analytical model is given in appendix B. The distribution of residual stresses for two different substrates and a wide range of cladding materials has been given. The key reasons of formation of residual stresses have been mentioned.

Chapter 5 - This chapter presents the development of 2D thermo-mechanical model using ANSYS'18 multi-physics platform. Model geometry, mesh, material

properties, optimisation of laser parameters are given. Finally, temperature distribution and residual stresses have been predicted for all cladding materials. The boundary conditions and assumptions are given in appendix C.

Chapter 6 - This chapter describes the development of a 3D thermo-mechanical model using ANSYS'18 multi-physics platform for deposition of Ti6Al4V cladding material on Ti6Al4V substrate. The geometry of model, mesh and its convergence, material properties, optimisation of laser parameters are given to achieve required condition of cladding. Finally, temperature distribution, melt pool size, shape, heating rate, cooling rate, micro-structure after cooling and residual stresses have been predicted. Additionally, model verification has been done to see the accuracy of the mesh and the applied boundary conditions. The boundary conditions and assumptions are given in appendix C.

Chapter 7 - This chapter focuses on the development of the 3D thermo-mechanical model for three cladding materials (Al_2O_3 -1, Al_2O_3 -2 and TiC) on Ti6Al4V substrate. Laser parameters were optimised for all cladding materials. After that, the prediction and comparison of temperature distributions and residual stresses distributions have been provided.

Chapter 8 – This chapter describes the summary of thesis and the possible direction of future research work.

1.3 Contribution to the Knowledge

The original contributions of this thesis are:

1. to provide a detail literature review on numerical simulation of Laser Cladding process and manifest future research areas in this sector.
2. describing temperature distribution, residual stress and strain distribution of the Laser Cladding process conceptually.

3. the prediction of residual stress in dissimilar material systems using a simple analytical model. This model can be used to compare the formation of residual stresses in dissimilar material systems where expensive multi-physics software is unavailable.
4. the development of two-dimensional and three-dimensional thermo-mechanical models of the Laser Cladding process for similar and dissimilar clad and substrate materials.
5. to optimise process parameters and predict temperature distribution and residual stress distribution using two-dimensional and three-dimensional numerical models for similar and dissimilar material systems. Additionally, heating and cooling rate, melt pool depth, heat affected zone and microstructure can be predicted from predicted temperature profile.
6. to understand the effect of temperature dependent material properties and temperature independent material properties on residual stress distribution.

2 Literature review

Low heat input, high solidification rate, excellent metallurgical bonding, deposition of functionally graded materials as well as rapid prototyping with homogenous structure made Laser Cladding (LC) a unique thermal coating process [1]. In the LC process, a laser heat source is utilized to deposit a thin layer (0.05-2 mm) of metal/ceramic, known as clad, on a solid substrate ranging from μm [14] to mm [15]. In the late 1970's, a clad was achieved by preplacing a layer of ceramic powders on a metallic substrate and melting these preplaced powders by using a laser heat source [1]. Almost a decade later in 1980, W. M. Steen and V. Weerasinghe introduced another process where powders are conveyed through a nozzle to the surface of substrate [1,9]. Concurrently, this process received an attention from the turbine manufacturing industry, where they started using it for hard-facing of turbine blade. Since then, the LC process is being used in various material processing industries for coatings [16], repairing [17], rapid prototyping [18] and making complex shapes.

In the LC process, the feeding of cladding materials can be performed using different methods. Depending on the ways of feeding, the LC process can be categorised into four types: preplaced powder system [19,20], coaxial powder system [21,22], off axis powder system [23] and wire feeding system [24,25], as shown in Fig. 2.1. Fig. 2.1 (a) shows the preplaced powder system. As the name suggest, powders are pre-placed on the substrate before applying the laser heat source. In the coaxial powder system, powders are delivered along the same axis (co-axially) of the laser beam, as shown in Fig. 2.1 (b). Fig. 2.1 (c) shows the schematic of off-axis powder system where powders are conveyed to the melt pool by a nozzle which is off axis to the laser beam. In the wire feeding system, wire is used as cladding material

instead of powders, as shown in Fig. 2.1 (d). The typical size of powders range from 50 to 150 μm [26,27] and the diameter of wire is around 1 mm [24].

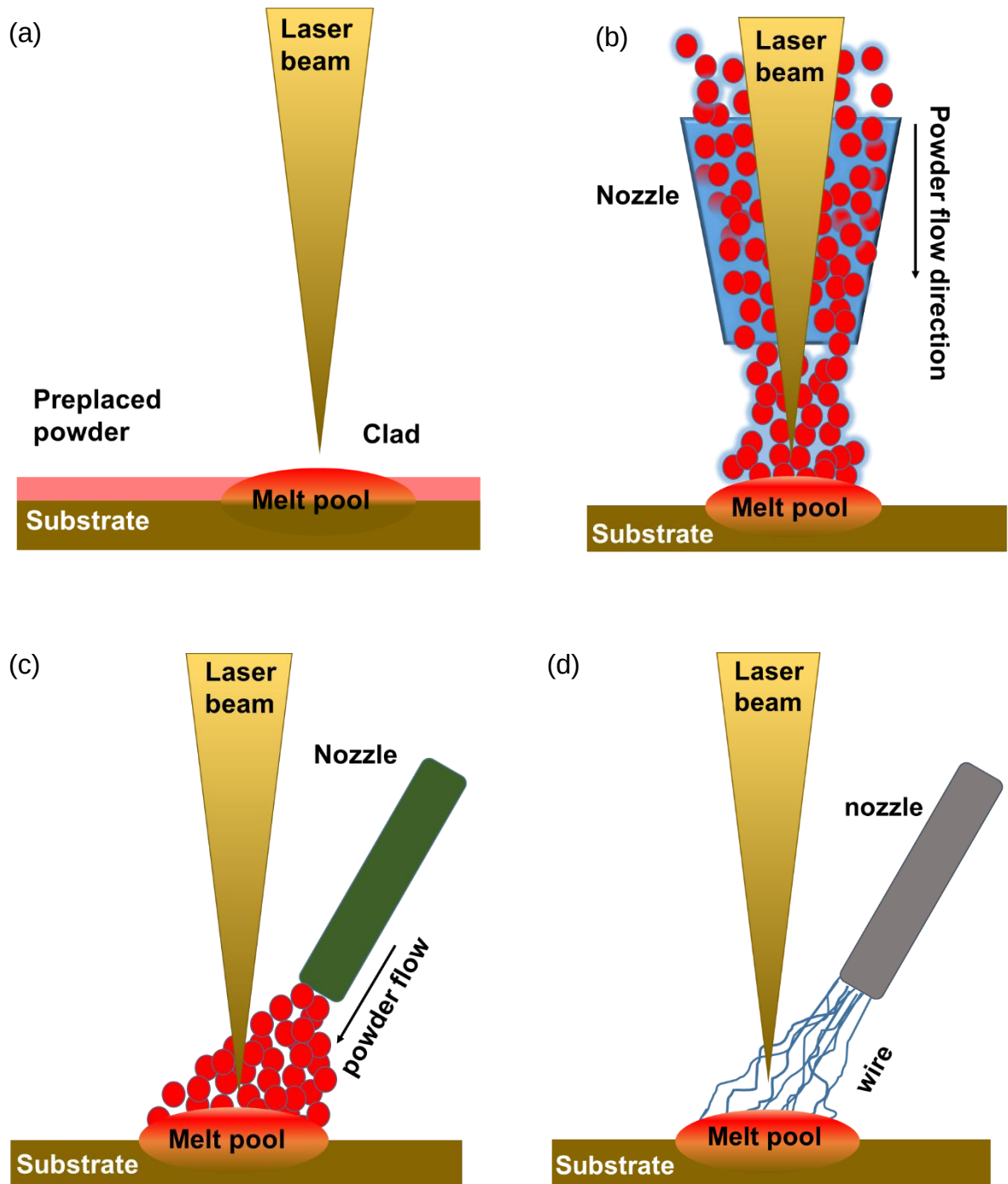


Fig. 2.1 Schematic diagrams of feeding system (a) preplaced powder system, (b) co-axial powder system, (c) off-axis powder system and (d) wire feeding system.

The coaxial LC process is more robust than other three feeding systems because it offers precise feeding rate in any direction. A 3D schematic diagram of a typical coaxial LC process is shown in Fig. 2.2 (a). In this process, a coaxial nozzle consists of powder feeder and laser system is moving in Z direction while powders are delivered along the Y axis. Coaxial nozzle moves with the laser beam at a certain scanning speed over a stationary substrate surface. A micrograph of laser cladded zone (clad), heat affected zone (HAZ) and substrate is shown in Fig. 2.2 (b) [10]. These three layers can be easily distinguished from each other by their texture.

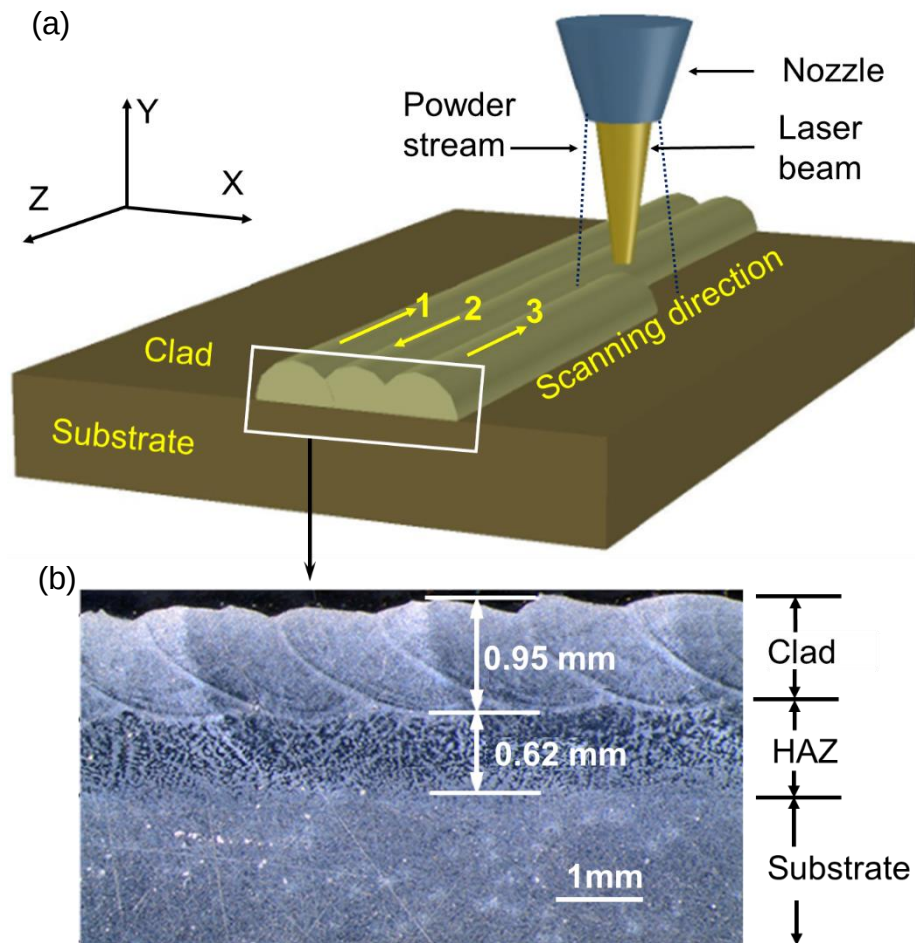


Fig. 2.2 (a) A schematic diagram of the coaxial Laser Cladding process, (b) micrograph, presenting deposited clad, HAZ and substrate area [10].

The LC process is carried out in three stages: powder flow dynamics, melt pool and clad properties. Complex phenomena such as powder flow behaviour, particle interactions with nozzle, laser and substrate, heat transfer and melt pool characteristics are difficult to understand from only experimental results. Therefore, several analytical models [28,29] and numerical simulations have been applied in three stages to understand those complex phenomena. The number of analytical models are still limited in number. Therefore, this chapter focuses on the development of the numerical modelling techniques which have been used to understand and predict the important features of the process physics and the coupling of different models. This chapter is divided into seven sections. Section one to three are based on simulations that have been applied in three stages (powder flow dynamics, melt pool and clad properties). Section one consists of interactions of powder with nozzle, laser and substrate, powder flow characteristics, effect of process variables on powder flow and model validation. Section two comprises of heat transfer in the melt pool, melt pool geometry and shape, flow characteristics of melt pool, and model validation. After that, the clad properties include simulations of phase transformation, microstructure, hardness and residual stresses, presented in section three. This section also includes model validation for the prediction of hardness and residual stresses. In section four, materials used in experimental work to improve surface properties and repairing have been given. Section five contains the relevance of laser cladding processes in additive manufacturing in relation to empirical, analytical and numerical models. After that, a future outlook of the LC process has been added in section six. Finally, section seven includes the conclusion and future prediction of LC process.

2.1 Powder flow dynamics

Powder flow dynamics is an important feature in the coaxial or the off axis powder feeding system as it can predict powder flow characteristics such as powder motion, powder flow profile, interactions of powder with laser system and thus used in optimization of process parameters. In these feeding systems, powders are carried by the drag force of the inert gas. Generally, the turbulent flow of carrier gas is considered as a continuum phase and hence solved using time averaged Navier-Stokes equations, whereas powders phase being dispersed in nature solved using Lagrangian equation [27,30–33].

The motion of gases were calculated using Eqs. 2.1-2.4 of conservation of mass [27,31,32] and momentum [27,30,31].

$$\nabla \cdot (\rho \mathbf{U}) = 0 \quad (2.1)$$

$$\partial / \partial t (\rho \mathbf{U}) + \nabla \cdot (\rho \mathbf{U} \mathbf{U}) = -\partial p / \partial X + \mu_t \nabla \cdot (\nabla \mathbf{U}) + f \text{ in X direction} \quad (2.2)$$

$$\partial / \partial t (\rho \mathbf{U}) + \nabla \cdot (\rho \mathbf{U} \mathbf{V}) = -\partial p / \partial Y + \mu_t \nabla \cdot (\nabla \mathbf{V}) + f \text{ in Y direction} \quad (2.3)$$

$$\partial / \partial t (\rho \mathbf{U}) + \nabla \cdot (\rho \mathbf{U} \mathbf{W}) = -\partial p / \partial Z + \mu_t \nabla \cdot (\nabla \mathbf{W}) + f \text{ in Z direction} \quad (2.4)$$

Where ∇ is the grad operator, ρ is the density of gas, $\mathbf{U}$ is the instantaneous velocity of gas field, t is time, U, V and W are the velocity component at X, Y and Z direction in turbulent flow, p is the pressure of gas, μ_t is the dynamic viscosity of gas and f is the external force acting on gas. In this method, gas is assumed as incompressible fluid.

The motion of powder particles is calculated using the equation 2.5.

$$m_p dv_p/dt = A_p C_D \rho_p / 2 (u - v_p) |u - v_p| + m_p g \quad (2.5)$$

where m_p is the mass of a particle, v_p is the velocity of particle, A_p is the area of particle, C_D is the drag coefficient, ρ_p is the density of the particle and g is the gravity force. To solve this equation, powders are assumed as solid, spherical and chemically homogenous. Moreover, the collision between particles are ignored. Furthermore, if powders while travelling from the nozzle exit to the substrate intersect the laser beam path, they absorb heat from the laser heat source. The transfer of heat from laser beam to powders is governed in the equation 2.6.

$$(1/3) r_p \rho_p C_p dT/dt = 1/4 (I_{dir} + I_{ref}) \eta_p - h(T - T_\infty) - \varepsilon \sigma (T^4 - T_\infty^4) - (1/3) \rho L_f r_p 1/dt \quad (2.6)$$

where r_p is the radius of particle, ρ_p is the density of the particle, C_p is the specific heat of powder, I_{dir} and I_{ref} are the energy coming from laser beam on the particle and reflected from substrate respectively, η_p is the absorption coefficient of particle, h is the heat convection coefficient, T is the temperature of particle, T_∞ is the temperature of the surrounding gas, ε is the particle emissivity and L_f is the latent heat of fusion. Here, the temperature gradient within particles are negligible as the biot number is less than 0.001. These equations are generally solved by computational fluid dynamic (CFD) technique using commercial software packages like CFD-ACE, CFD fluent and ANSYS fluent.

2.1.1 Modelling of powder flow characteristics

The characteristics of the powder flow is affected by interactions of powders with nozzle, laser irradiance and substrate. Therefore, based on these interactions, the simulation of entire powder flow is carried out in three distinct zones namely powder-nozzle [34,35] powder-laser [27,36–39] and powder-substrate [27], shown by a, b and c respectively in Fig. 2.3.

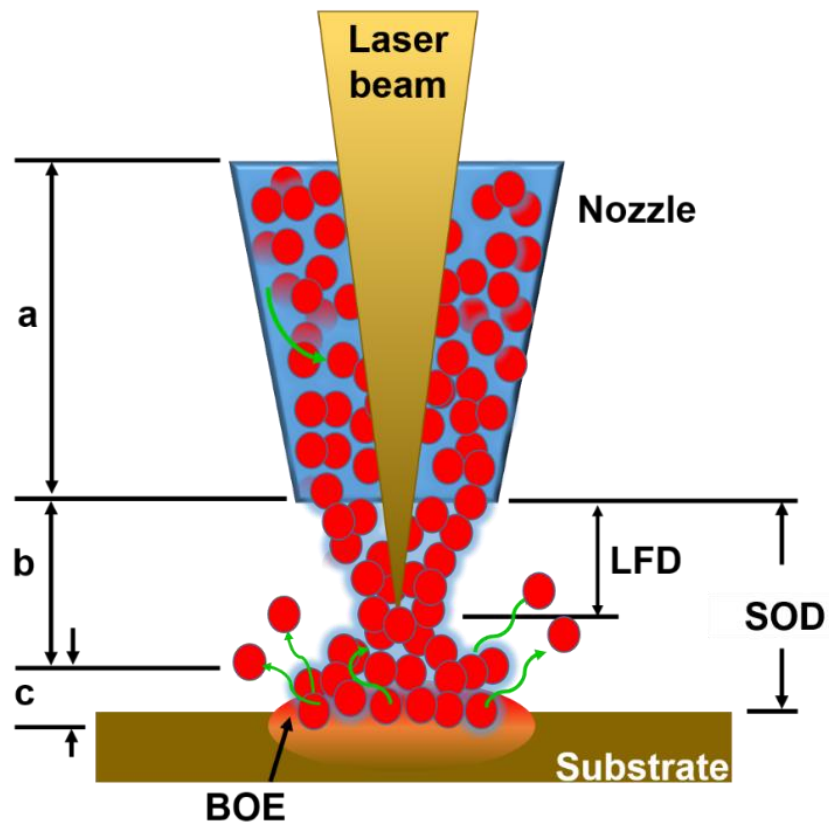


Fig. 2.3 Schematic diagram of several interaction zones along the laser beam to substrate. The interactions can be divided into three zones such as (a) powder-nozzle [42,47], (b) powder-laser [30,47,49,51] and (c) powder-substrate [30]. LFD = laser focus distance, SOD = stand off distance, BOE = bounce off effect.

2.1.2 Powder-nozzle interaction zone

In powder-nozzle interaction zone, particles experience a collision with the walls of the nozzle as they are dragged by the carrier gas. Depending on the loss of energy of the particle on collision, two types of collisions have been described in literature, i.e. elastic and inelastic collision [35]. In the elastic collision, there is no energy loss whereas the energy loss takes place in the inelastic collision [40].

Powders coming from the nozzle exit form powder flow stream. Typically, powders flow expands at the exit of the nozzle due to gravity and flow of gases which merge into a convergence point after a certain distance, and diverge again. Therefore, the distribution of powder in the powder flow near the exit point of nozzle and at the convergence point is considered to be of annular and Gaussian shape respectively [32,33,41,42]. Nevertheless, the flow characteristics depend on nozzle geometry, shape and size of powders, environmental pressure and type of carrier gas. Nozzle geometry is one of the significant parameters which controls the flow characteristics [43,44]. The inward position of middle nozzle converge powders around 5 mm away from the nozzle exit whereas the outward position shift the converge point to 8 mm [43]. Additionally, the concentration of powder increased up to 50% by using outward position of middle nozzle [45]. The difference of nozzle angles also has impact on the concentration of powder in the distribution. Zhang et al. investigated the concentration of powders for three different nozzle angles. 45, 60 and 70 [46]. The maximum concentration of powders at the convergence point was achieved using 60° nozzle angle over 45° and 70° nozzle angles [46]. Another parameter is particle size which effect on the trajectory of the powders flow. For example, finer powders (less than 10 μm) were difficult to converge than coarse powders (more than 100 μm) [33], because the trajectory of finer particles easily shifted by gas flow

than heavy particles. Moreover, the concentration of particle in the powder stream was lower in case of larger particle due to higher gravity force. Another study by Smurov et al. showed that the trajectory of coarse particle was more dispersed than finer particles due to the collision with the nozzle [35].

The shape of powders is considered spherical in most simulations but the non-spherical powders can alter the results of powder concentration in the distribution [45]. The results of simulation with non-spherical particles matched well with the experimental results whereas spherical powder overestimated the peak concentration value in powder flow [32,42].

The velocity of powders is affected by density and compressibility of carrier gas [46]. For example, the use of helium increased the velocity of powders over the argon due to its lower density and higher compressibility [46].

2.1.3 Powder-laser interaction zone

In powder-laser interaction zone, due to the interaction between particle and laser beam, the laser energy gets attenuated by reflection, absorption, radiation and beam scattering. In literature, several models based on ray tracing procedure [37], shadow model [47], resolution model [48] and light propulsion force model [49,50] are reported to predict the attenuation of laser energy. Total heat transfer phenomena consists of energy absorption of particles from laser heat source, heat conduction in the powder and heat dissipation to the environment from the particle by convection and radiation. The internal conduction in powders is taken based on biot number [49–52]. Recently, liquid fraction evolution during the phase change under the laser irradiation has been considered [53]. The absorbed laser power increases temperature in the powder flow distribution which adds additional thermal

energy to the melt pool. The energy balance equation for the temperature distribution of particle is given in Eq. 6. The temperature distribution of powder flow is highly dependent on laser power [39] and the distance between the nozzle exit and the focal point of lens (marked as LFD in Fig. 2.3) [52]. The peak temperature of powders increased with increasing laser power. However, for very high laser power, particles tends to vaporise, thus causing approximately 25% reduction in powder mass [39]. LFD is one of the controlling factors of laser power absorption. Therefore, by optimization of LFD, homogenous temperature in the distribution can be achieved which increases the deposition efficiency [52].

2.1.4 Powder-substrate interaction zone

In early stage of simulation, the substrate was not considered in the simulation of powder flow [31]. The consideration of the position of substrate affect the powder flow characteristics. The distance between the position of the top surface of the substrate and the exit of the nozzle is called the stand-off distance (SOD) as shown in Fig. 2.3. Therefore, SOD has a significant effect in the interaction of powder and substrate [43]. For example, to produce high quality clad, the convergence point of powders should be equal to SOD [43]. Medina et al. showed that the higher concentration was obtained due to bounce off of particles from the substrate when the substrate was positioned near the nozzle exits [27]. The chronological development of models in powder flow dynamics, their focus, model type, used software, clad/powder materials and assumptions has been summarized in Table 2.1.

Table 2.1 The chronological development of numerical models on powder flow dynamics for co-axial powder type.

Ref.	Focus of the work	Model type	Software used	Material (clad or substrate) / Size (μm) / shape	Shortcoming in the model
Lin et al. [31] 2000	Simulated powder flow structure by varying arrangement of nozzle exit	2D	CFD FLUENT	Stainless steel / 45-105 / spherical	The collision among particles, the interaction of particles with nozzle wall and laser beam were ignored.
Pan et al. [45] 2005	Developed a numerical model of metallic powder flow with non-spherical powder considering interaction of powders with nozzle wall	3D	Not mentioned	Iron / 100 / non-spherical	No carrier gas was considered in the powder flow.
Zekovic et al. [30] 2007	Simulated a gas-powder flow using radially symmetrical nozzle	3D	FLUENT	H13 tool steel / 45-180 / spherical	The collision of particles and the interaction of particles with laser beam was ignored.
Wen et al. [32] 2009	Predicted a powder flow in and after the nozzle considering various particle morphology and size	3D	CFD FLUENT	Stellite 6 / 45-180 / non-spherical	Particles collision and laser attenuation were not considered.
Tabernero et al. [41] 2010	Developed a general model for any kind of material considering powder feed rate and powder size	3D	CFD FLUENT	Stainless steel / 45-150	The interaction of powder with nozzle wall, laser beam and substrate are not considered.

					Inconel / 40-110 / spherical in both case	
Ibarra-Medina et al. [27] 2011	Developed a numerical model of powder flow considering interaction of powder with laser beam and substrate	3D	CFD-ACE+	Stainless steel / 53-150 / spherical	The collision of powder with nozzle wall was ignored. The carrier gas velocity, different kind of carrier gas and material effect were ignored.	
Nie et al. [54] 2014	Predicted powder flow distribution considering various particle size	3D	ANSYS FLUENT	Inconel 718 / 50-200 / spherical	Model ignored the presence of substrate and energy loss due to interaction with wall.	
Zhang et al. [46] 2016	Developed a powder flow to investigate environmental pressure ,vacuum effect and different carrier gas effect on the powder flow distribution	3D	ANSYS	Titanium / 50 / non-spherical	All kinds of interactions were ignored.	
Kovalev et al. [40] 2017	Predicted a powder flow considering inelastic collision of particle with the nozzle wall for different substrate position	3D	FLUENT	Steel / 60 / spherical	The nozzle design, carrier gas parameters and collision between particles are ignored.	

2.1.5 Experimental validation

In literature, predicted powder flow characteristics such as the maximum concentration of powders, the position of maximum concentration, the shape of powder flow from nozzle exit to substrate and velocity of powders have been validated experimentally using image capturing techniques.

The maximum concentration of powder in the flow was predicted considering non-spherical particle collision and nozzle wall roughness for various nozzle geometry such as inward middle nozzle, outward middle nozzle [45]. In experiment, light was used to illuminate powder particles at the vertical cross section of the powder flow and images were captured using a high speed camera. Then, object detection process was used to extract powders concentration from the captured images. Maximum 20% mismatch was observed between experimental and simulated results for outward middle nozzle. This mismatch was attributed to the difficulty in distinguishing the individual particle by image processing method, especially in the concentrated region where particles tend to overlap with their neighbour.

Zekovic et al. experimentally verified the position of maximum powder concentration [30]. The cylindrical pattern of the maximum powder concentration along the vertical axis in the SOD range was found from simulated results. Experimentally, powder concentration was determined by measuring the intensity of scattered light using a charged couple device (CCD) sensor. The measured result showed same range as obtained in simulation. CCD sensor was also used to measure powder distribution at different plane [41]. The experimental results showed an annular shape at the nozzle exit and Gaussian shape near the powder flow convergence plane which corresponded with simulation [41].

Balu et al. developed a model to predict the velocity of three different particles (NT-20, NT-80, and WC) at the nozzle exit and validated their simulated results experimentally [55]. A high speed CCD camera was used to measure the position of particle with time in the powder stream which was illuminated by a green laser of 532 nm wavelength. The simulated velocity of NT-20, NT-80, and WC was 8.98 m/s, 7.69 m/s and 7.19 m/s respectively whereas the measured velocity was 10.1 m/s, 8.48 m/s and 6.87 m/s respectively. In case of WC powder, the simulated velocity was higher than the measured value while other two cases showed opposite trend. However, the differences between the simulated and experimental results in all three cases were consistent.

2.2 Melt pool

The melt pool constitutes another discrete part of the entire process. It focuses on heat transfer [42,56–58], melt pool geometry, melt pool shape [59–62] and fluid flow velocity [32,42,56,58,63–65]. In order to predict these dynamic phenomena numerically, level set method [32,58,63,66,67], volume of fluid method [23,56,59,60,64,68–70], finite element method [21,71–76] and finite difference method [39] have been adopted in various commercial multi-physics platforms such as ANSYS, FLUENT, ANSYS-CFD, ABAQUS and COMSOL. This section gives the overview of development in simulation to predict aforementioned parameters of melt pool and experimental validation techniques.

2.2.1 Heat transfer in melt pool

The first step in simulating temperature distribution in melt pool is to define the laser heat source which can be generally categorised in two types: pulse or continuous.

The equations applied in simulation for pulse [74] and continuous [10,77] laser heat source as surface heat flux are defined in Eqs. 2.7-2.8.

$$\text{Pulse, } Q_{(x,y)} = P/\tau_t \pi R^2 \exp(-2r^2/R^2) \quad (2.7)$$

$$\text{Continuous, } Q_{(x,y)} = \eta P/\pi R^2 \exp(-2r^2/R^2) \quad (2.8)$$

where Q is the laser heat source, P is the laser power, τ_t is the pulse duration, R is the radius of laser beam, η is the absorptivity of laser power and r is the radial distance from the centre of laser heat source.

In simulation, laser heat source was similarly applied as volumetric heat source [63] what is expressed in the equation 2.9.

$$\text{Continuous, } Q_{(x,y,z)} = 6\eta P/\pi\sqrt{\pi}R^3 \exp(-3r^2/R^2) \quad (2.9)$$

where Q is the laser heat source, P is the laser power, R is the radius of laser beam, η is the absorptivity of laser power and r is the radial distance from the centre of laser heat source.

In literature, predominantly the Gaussian heat source [43,71,73,78–83] is used. However, Tseng et al. developed another heat source named tailor heat source considering the physical characteristics of laser source such as beam diameter, wave length, mode and focusing length [84]. The application of tailor heat source induced high intensive energy which produced high temperature in clad and substrate. The transient temperature distribution was predicted using conduction while convection and radiation were applied as boundary conditions. The conduction equation of laser heat source of this process can be seen in Eq. 2.10.

$$\partial(\rho C_p T)/\partial t + \nabla \cdot (\rho C_p \mathbf{u} T) = \nabla \cdot (k \nabla T) + Q_{laser} \quad (2.10)$$

where ρ is the density of gas, C_p is the specific heat capacity, ∇ is the grad operator, u is the velocity of laser head, k is the thermal conductivity, ∂T is the particle temperature variation in the time ∂t and Q_{laser} is the heat flux from laser heat source.

Heat transfer simulations are mainly done in preplaced and coaxial powder system. The temperature distribution in both cases depends on laser heat source characteristics such as laser power, scanning speed, beam diameter, heat source mode and focusing point of beam. The additional investigated process parameters are powder bed thickness and feed rate for preplaced and coaxial powder system respectively.

In preplaced powder process, heat source was directly applied on the surface of preplaced powder [73]. Guo et al. studied the effect of laser power for proper melting of cladding material and certain portion of the substrate [72]. According to authors, below 240 W laser power, the clad could not form due to the lack of fusion whereas above 530 W laser power, material vaporized leading to poor clad quality. Moreover, laser power also controls dilution rate in the system. The dilution was increased from 6.25% at 2500 W to 33.75% at 3000 W which is detrimental for the clad [82]. The desirable dilution is around 3-8%. Another model showed the effect of heat source on the peak temperature. The predicted peak temperature for TEM₀₀ Gaussian mode, a TEM₀₁ single mode and a tailored TEM_{mixed} multi-mode were 7115°C, 3108°C and 2191°C respectively due to the different concentration of energy in the heat distribution [84]. The effect of powder bed thickness on the melt pool area was studied. It was observed that with increasing thickness of powder bed, area of melt pool increased while height decreased [85].

In the coaxial powder system, powder flows along the same axis of the laser heat source. Therefore, models for the coaxial feeding system use birth and kill technique to deposit clads. In birth and kill technique, elements must be killed in the clad area before applying any heat source and then deactivated elements remained in the process with near zero conductivity. When the heat source was applied on a specified location of the surface, the killed elements on that position in the clad area were activated. Using this technique, Hao et al. developed a finite element model (FEM) to simulate the temperature distribution in LC [71]. This model was capable to predict temperature distribution with varying laser power, laser scanning speed and powder feed rate. Another study showed that increment of laser power (500 W) increased the temperature by 249°C [86]. Farahmand et al. reported a model which calculated cooling rate at various the preheating temperature of the substrate [87]. Though, the peak temperature was increased with increasing the preheating temperature of the substrate, more stable melt pool was obtained because of slower thermal gradient. The addition of clad layer also increased the peak temperature of melt pool [10,62,88]. The same phenomenon was observed for the deposition of overlapped clad [56] and double track deposition [89]. Models mentioned in this section did not consider the effect of fluid flow, interaction of powders and substrate on the melt pool temperature. The high cooling rate solidify the molten material within fraction of second which limited the effect of fluid flow in the melt pool. The predicted temperature distributions in preplaced and co-axial powder flow system using FEM are given Fig. 2.4.

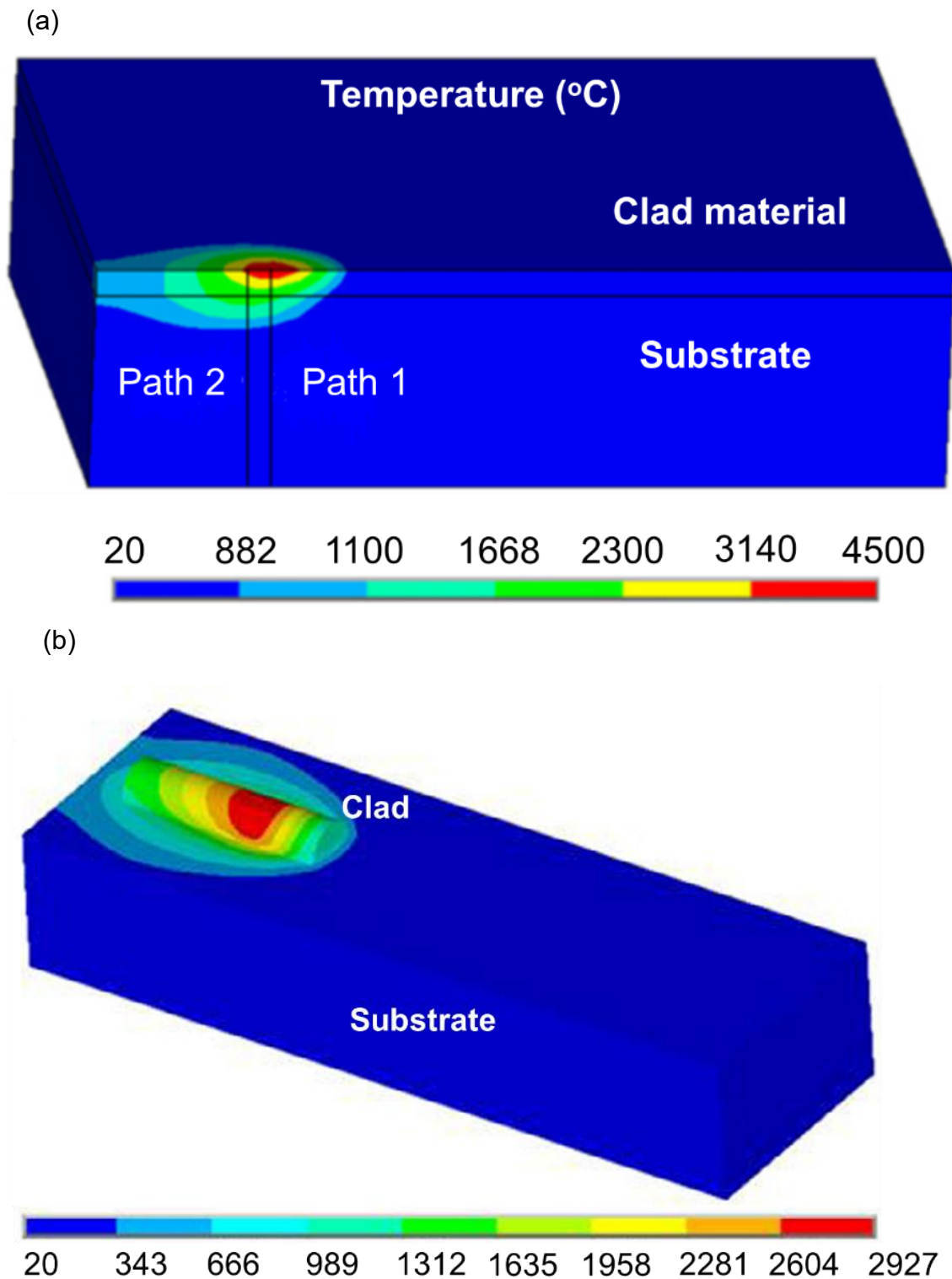


Fig. 2.4 Three dimensional temperature distribution of (a) preplaced [73] and (b) coaxial powder system [71] using FEM.

2.2.2 Melt pool geometry and shape

The melt pool geometry and shape were predicted from temperature distribution profile and analytical functions of melt pool shape respectively. The typically used functions in literature are elliptical cylinder function [87,88], circular arc [90] and parabolic shape function [62] which calculate the melt pool boundary. The parameters that influence the geometry and shape of the melt pool are laser-powder interaction time, laser power, powder catchment efficiency, powder feed rate and laser scanning speed. The melt pool width and depth were found to increase with increasing the interaction time with laser beam [56,61,62] and laser power [21,24,56,57,61,62]. On the other hand, the resulted clad height was relatively constant with increasing the laser power [56,91]. Partes et al. [26] and Ya et al. [62] predicted the melt pool geometry by taking into account of laser power and powder catchment efficiency. Moreover, the increment of powder catchment efficiency changed the heat conduction process which altered the shape of the melt pool [92]. Both height and width increased with increasing feed rate in the process [21,24,63,64] while an opposite phenomenon was observed with increasing the laser scanning speed [21,63,68,93]. More importantly, the roughness of the melt pool surface also depends on process parameters. It was reported that the lower laser power, lower scan speed, lower temperature of particle and substrate produced a smoother clad surface [68].

2.2.3 Fluid flow in melt pool

Marangoni force, the injected powders force and angle of melt pool surface determine the pattern and direction of molten fluid [42,56,63]. Surface tension between molten fluid and air is the origin of Marangoni force [65,94]. This Marangoni force transports the molten fluid from the laser centre point to the periphery of the

melt pool, and consequently, form vortex in the melt pool [42,60,63]. Subsequently, the velocity of fluid decreased when molten fluid enter to the mushy zone due to the lower mobility of atom [42]. The addition of injected powder force with Marangoni force in coaxial powder feeding system increased the number of vortex, decreased the size of melt pool and changed the direction of fluid flow from the periphery to inward direction [59,63,64]. Since the fluid flow turned to inward direction from the surface, facilitated the transportation of the higher energy fluid to the bottom of the melt pool and increased melt pool depth. The fluid flow behaviour became more complicated during the deposition of multi-layer clad [56,66,69]. In this process, as cladding material was deposited on the top of the deposited clad, the angle between surface and clad was decreased. Lee et al. reported that with increasing the number of layers, the angle decreased at the top surface resulting lower velocity at the top layer melt pool [56]. The reported surface velocity decreased from 8.59 cm/s at first layer to 5.05 cm/s at third layer. The liquid flow is considered as incompressible Newtonian with laminar flow [60]. The governing equations of conservation of mass and momentum to solve the fluid flow in melt pool are given in Eqs. 2.11-2.14

$$\partial/\partial t (\rho) + \nabla \cdot (\rho \mathbf{V}) = 0 \quad (2.11)$$

$$\partial/\partial t (\rho u) + \nabla \cdot (\rho \mathbf{V} u) = \nabla \cdot (\mu_l (\rho/\rho_l) \nabla u) - \partial p/\partial X - (\mu_l/N)(\rho/\rho_l)(u - u_s) + S_x \text{ in X direction} \quad (2.12)$$

$$\partial/\partial t (\rho v) + \nabla \cdot (\rho \mathbf{V} v) = \nabla \cdot (\mu_l (\rho/\rho_l) \nabla v) - \partial p/\partial Y - (\mu_l/N)(\rho/\rho_l)(v - v_s) + \rho g + S_y \quad \text{in Y direction} \quad (2.13)$$

$$\partial/\partial t (\rho w) + \nabla \cdot (\rho \mathbf{V} w) = \nabla \cdot (\mu_l (\rho/\rho_l) \nabla w) - \partial p/\partial Z - (\mu_l/N)(\rho/\rho_l)(w - w_s) + S_z \quad \text{in Z direction} \quad (2.14)$$

where ρ_l is the density of liquid material, ∇ is the grad operator, $\mathbf{v}$ is the velocity vector of liquid material, u, v and w are velocity component of liquid material in X, Y and Z, u_s and w_s are the tangential velocity at free surface, v_s is the normal velocity at the free surface, g is the gravity force, S_x, S_y and S_z are the source of momentum per unit volume per unit time in X, Y and Z direction. In this method, fluid in melt pool was considered as compressible. Materials were assumed chemically homogenous and powders were assumed molten at the time it entered in the molten pool. Additionally, laser beam was assumed to be a Gaussian distribution.

The progress of simulation of thermal models to date have been summarized in Table 2.2. The contents of this table are the focus of work, applied methodology, materials used as clad and substrate.

Table 2.2 Chronological development of thermal model in melt pool.

Ref.	Focus of work (method)	Material	Shortcomings in model
		Substrate / Clad	
Hoadley et al. [77]1992	Developed a thermal model to determine the temperature distribution considering the effect of laser power and laser scanning speed (in house coding)	Mild steel / cobalt based alloy	This model was restricted to two dimension.
Guo et al. [72] 2003	Simulated temperature profile considering the contact resistance between powder bed and the substrate (FEM)	ZM51 magnesium alloy / Al-12%Si alloy	The thermal properties of materials were considered constant even at high temperature.
Palumbo et al. [95] 2004	Predicted the temperature distribution in ring geometry (FEM)	Aluminium / copper alloy	The melt pool flow was not considered.
Choi et al. [64] 2005	Developed a 2D thermal model considering solidification, melting and evaporation phenomena of materials	Mild steel / H13 tool steel	Material properties were temperature independent.

Lei et al. [82] 2010	Developed temperature distribution of composite material (FEM)	Ti6Al4V / TiC-NiCrBSiC	The effect of latent heat, convection of liquid metal and temperature dependent composite material properties were ignored.
Holfman et al. [23] 2011	Developed a thermal model to predict the geometry of melt pool	Stellite 12 / mild steel	The melt pool flow was not considered.
Cheikh et al. [81] 2012	Developed a thermal model to predict the clad geometry (FEM)	Low carbon steel / 316L stainless steel	Material temperature dependent properties were accounted using Heaviside function.
Tseng et al. [84] 2013	Predicted the transient temperature distribution using a tailor heat source can be applied to other laser materials process simulation (FEM)	Medium carbon Steel S45C / cobalt based stellite 6	The fluid flow effect on the temperature distribution was not accounted.
Hao et al. [71] 2013	Simulated the temperature distribution using an inverse modelling approach (FEM)	Ti6Al4V / Ti6Al4V	The chemical reaction and fluid flow effect on the temperature distribution was not accounted.
Farahmand et al. [88] 2013	Developed a thermal model using top-hat power distribution (FEM) to predict temperature distribution	Mild-steel / AISI H13 powder	The chemical reaction between the materials was ignored.

Raju et al. [96] 2014	Predicted the temperature distribution varying laser scanning speed (FEM)	Nickel super alloy / Nickel super alloy	Phase transformation, latent heat of fusion and vaporization were not considered.
Nie et al. [54] 2015	Predicted the transient temperature distribution to calculate thermal cycles (FEM)	Inconel 718 / Inconel 718	The effect of convection of liquid metal was not considered in the thermal model.
Ya et al. [62] 2016	Developed a thermal model taking into account of powder stream density and powder efficiency to predict the clad geometry (FEM)	DIN steel / Stellite 6	The clad geometry was calculated by the function of parabolic shape. The laser power should be reduced gradually to maintain the substrate temperature which was not considered.
Lee et al. [97] 2016	Predicted the temperature distribution for single and multi-layer clad (VOF)	IN718 / IN718	The peak temperature was restricted to liquidus temperature. Temperature dependent material properties was not used.
Masoomi et al. [98] 2017	Developed a thermal model using multi-laser system (FEM)	Ti6Al4V / Ti6Al4V	The wetting behaviour of liquid and solid, solid phase nucleation and pore generation were not accounted.
Nazemi at al. [99] (2018)	Used imposed thermal cycle (ITC) method to predict the temperature distribution.	AISI 1918 / P420 stainless steel	The fluid flow effect on the temperature distribution was not accounted.

2.2.4 Experimental validation

The simulations found in literature related to the melt pool dynamics mainly focused on the prediction of velocity of fluid flow, temperature distribution and dimension of melt pool. Out of these parameters, the measurement of the velocity of fluid flow in the melt pool is difficult due to its quick solidification process. The temperature distribution of the melt pool has been measured using pyrometers, thermocouple and micrographs. Pyrometers are used to measure the peak temperature and the temperature gradient on the surface from the thermal radiation of a heated object [100,101]. Kohler et al. used pyrometers to validate the simulated peak temperature [101]. In comparison to the predicted peak temperature (2424°C), the experimental result saturated at 1900°C due to the calibration limit of pyrometer. Another process to measure temperature distribution is using thermocouple. A type-K thermocouple, located 3 mm below the surface of substrate was used to record the transient temperature [102]. The results from experiments agreed well with the predicted results. Lei et al. validated the predicted temperature distribution from the SEM micrograph for the deposition of TiC/NiCrBSiC clad on Ti6Al4V substrate [82]. In this work, based on the predicted temperature, authors divided the molten pool region in two separate areas called TiC melting area and TiC partially melting area. In TiC melting area, as the name suggests, the simulated temperature range (3140°C to 4200°C) was higher than the melting temperature (3140°C) of TiC. In TiC partially melting area, the predicted temperature range (from 1668°C to 3140°C) was above the melting temperature (1668°C) of NiCrBSi and below the melting temperature (3140°C) of TiC. Therefore, in TiC partially melting area, NiCrBSi was melted but the TiC was partially dissolved. The cross section morphology of a single clad track in the SEM micrograph showed precipitated TiC particles and dendrites

in TiC melting section and undissolved TiC particles in TiC was partially dissolved section. The observation of microstructure confirmed the temperature distribution obtained from simulation.

In order to validate the shape of the melt pool, micrographs of clad had been used. Y. Lei et al. validated the predicted depth of melt pool (0.76 mm) with the micrograph of the clad which showed 0.8 mm depth of melt pool [82]. In another work, Hofman et. Al. used CCD camera and image processing technique to capture the real time dimension of the melt pool [23]. The simulated width and length were 2.77 mm and 3.92 mm respectively while the measured width and length were 2.98 mm and 3.96 mm. Simulation and experimental results showed good agreement.

2.3 Clad properties

This section reviews the simulation to predict properties of clad such as phase transformation, microstructure, hardness, residual stresses, and finally the experimental procedures to validate the simulation results.

2.3.1 Modelling of clad properties

The simulation of clad properties are performed in conjunction with thermal model. In literature, two types of phase transformations are mentioned: diffusional phase transformations and diffusionless phase transformations [103]. In case of diffusional phase transformations, Johnson-Mehl-Avrami equation was used while diffusionless phase transformations is coded with Koistinen-Marburguer equation [103]. Both of the equations are used for the non-isothermal phase transformation. Johnson-Mehl-Avrami equation is defined as in Eq. 2.15.

$$f' = 1 - \exp(-mt^n) \quad (2.15)$$

where f' is the volume fraction of the new phase, m is a coefficient dependent on the temperature, composition of parent phase, and grain size t is the isothermal time duration and n is a coefficient dependent on the type of phase transformation and grain growth.

The expression of Koistinen-Marburguer equation is given in Eq. 2.16.

$$f'' = 1 - \exp(-c(M_s - T_\beta)) \quad (2.16)$$

where f'' is the instantaneous volume fraction of the new phase, the value of c is 0.003, M_s is the the martensitic transformation temperature and T_β is the beta transus temperature.

For non-isothermal phase transformation, Johnson–Mehl–Avrami–Kolmogorov equation was used to predict the fraction of crystallized volume [104], expressed Eq. 2.17.

$$f'''(T(t)) = 1 - \exp \left\{ - \left(\int_{t_o}^{t_e} K(T(t)) dt \right)^e \right\} \quad (2.17)$$

where f''' is the volume fraction of the new phase for non-isothermal phase transformation, t_o and t_e are initial and end time of phase transformation, K is the temperature dependent crystallization rate, t is the phase transformation time duration and e is the the dimensionality of growth of phases.

The solidification of dendritic microstructure has been simulated based on Kurz-Fisher and Trivedi theory [105]. It was shown that the rate of solidification increased with increasing cooling rates till it reached the critical value. Beyond the critical value of the cooling rate, the growth of nuclei hindered due to the inability of atom to diffuse. Therefore, the growth of nuclei was slower even at higher cooling rate [105]. In another work, the effect of process variables on the cooling rate was studied [106].

For example, with increasing the laser scanning speed, cooling rate decreased. Additionally, it was observed that lower cooling rate produced smoother clad surface [67].

Hardness of clad can be predicted by coupling thermo-kinetic relation with the thermal model [107,108]. In this model, the volume fraction of phases after thermal treatment and the hardness of each phases are required. The volume fractions of phases are calculated from the phase diagram, the cooling temperature from the thermal model and hardness of each phases are taken from the literature to calculate the hardness of total volume. The estimation of hardness through nanoindentation process was reported by Gu et al. [109]. They developed a FEM model of nanoindentation on particle to produce load vs displacement graph. From this graph, depth of penetration was calculated, which is related with contact area of indenter. Finally, hardness was predicted from the applied load and the contact area.

In laser deposition process, residual stresses are generated in the deposited parts which causes the formation of crack and distortion. Therefore, prediction of residual stresses is an important area in simulation of the Laser Cladding process. Most of the simulations of predicting residual stresses in clad and substrate have been performed using finite element method [88,110–113]. In the early stage of simulation, elastic strain, plastic strain and thermal strain were considered to calculate residual stresses [10,111,114]. Later, phase transformation and volumetric strain increment were added in the calculation of residual stresses for more accurate analysis [88,115]. The governing equation to predict total strain, by assuming that there is no stress in the substrate before applying laser heat source is given in the following equation.

$$\varepsilon = \varepsilon^{el} + \varepsilon^{pl} + \varepsilon^{th} + \varepsilon^{\nabla V} + \varepsilon^{Trp} \quad (2.18)$$

Where, ε^{el} , ε^{pl} , ε^{th} , $\varepsilon^{\nabla V}$ and ε^{Trp} are elastic, plastic, thermal, volumetric and phase transformation strain respectively.

The generation of strain depends on materials properties such as Young's modulus, Poisson ratio, yield strength and tensile strength. Few research groups used temperature independent material properties [114,116,117] while others used temperature dependent material properties for more accurate results [88,110,118].

In literature, residual stresses in normal direction and Von Mises stresses have been predicted in single track, multi-tracks and overlapped clads. Mainly, tensile residual stresses were found in the clad area and small part of the substrate from the interface in single clad [110,114,119]. This tensile stress was balanced with the compressive stress inside the substrate. For practical applications, multi-tracks and overlapped clads were deposited to observe the change of residual stresses [10,88,120]. In the multi-tracks deposition, maximum tensile stresses were located at the last track due to high cooling rate while it was reduced in previously formed track due to the relaxation of heat treatment [10,88]. In case of overlapped clad, the resistance of formation of cracks increased as the surface of previously formed clad got melted and decreased the tensile residual stresses [120]. The residual stress distribution for single clad using FEM is shown in Fig. 2.5.

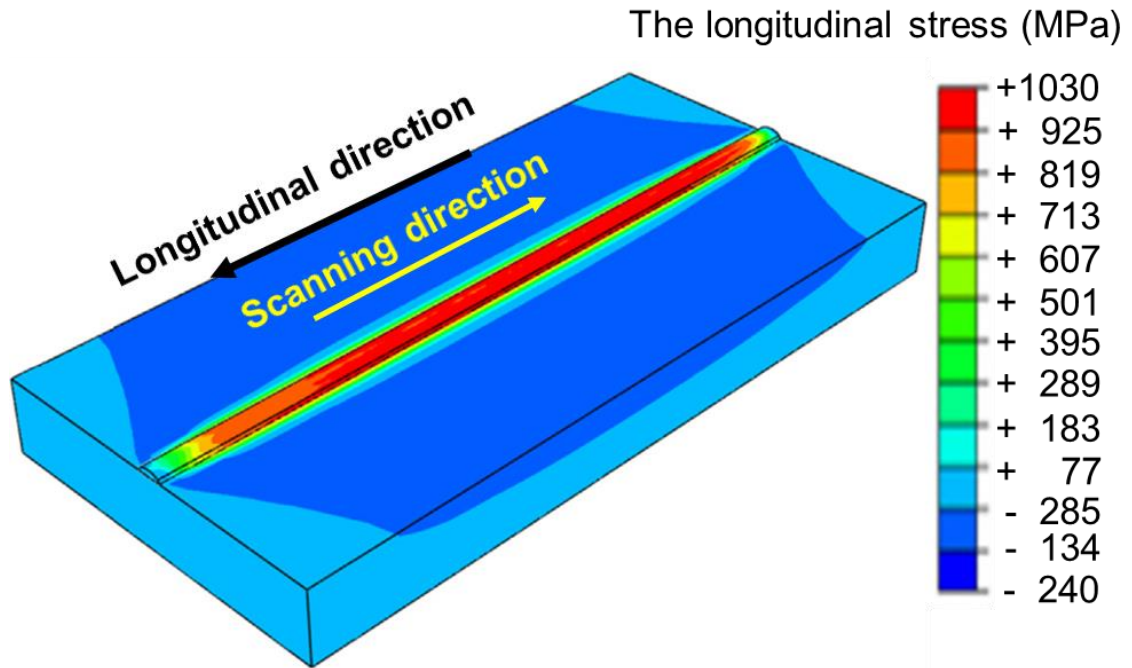


Fig. 2.5 Predicted residual stress distribution in longitudinal direction using FEM [10].

The detrimental tensile residual stresses reduce the fatigue strength of the mechanical components. Y. Chew et al. have developed a model to predict fatigue life based on crack closure model [121]. This model estimated the fatigue life of the clad having multiple surface cracks.

2.3.2 Experimental validation

The predicted clad properties such as hardness and residual stresses have been experimentally validated. Hardness is usually measured using digital micro-hardness tester and nanoindenter whereas X-ray diffraction (XRD) is mainly used for residual stress measurement.

The simulated hardness was validated from the measurement of the digital micro-hardness tester (CLARK-700 AT) [108]. It calculated the Vickers hardness automatically from the diagonal length of indentation. The measured hardness

showed a similar trend with the predicted hardness in the clad (from 671 HV to 649 HV) and the dilution zone (649 HV to 615 HV). In another study, the predicted hardness was validated from the results of a nanoindenter test [109]. This device, equipped with AFM, was used to measure the load and the displacement towards the indenter and into H13–TiC composite coatings. The hardness was calculated from the contact area and applied load. The measured and predicted hardness of TiC particle in the coating were 30 ± 5 GPa and 38.2 ± 3.7 GPa respectively. The hardness of H13 matrix was same around 9 ± 2 GPa for both simulation and experiment.

In literature, the predicted residual stress has been predominantly validated using XRD [114,122]. In this method, the residual stress was calculated from a diffraction pattern. The calculated stress from XRD at the clad top, at the interface and in the substrate were 300 MPa compressive stress, 250 MPa tensile stress and 330 MPa compressive stress respectively. In comparison, the simulated stress at the clad top, at the interface and in the substrate were 290 MPa compressive stress, 470 MPa tensile stress and 105 MPa compressive stress respectively [114]. The higher compressive stress at the top of the clad, lower tensile stresses at the interface and higher compressive stress in the substrate were obtained in the XRD results. The reason of the deviation could be attributed on two factors: (a) XRD provides an average value; (b) multiple clads were deposited on the same substrate.

2.4 Materials

Material selection is one of the important factors in the Laser Cladding process in order to determine the compatibility between clad and substrate, application and enhanced properties. The mainly used substrate materials are alloy while clad materials are metal, alloy and ceramics. The application of this process is to produce the mechanical components of aerospace, automobile and biomedical industries. The materials in simulation work are presented in table 4. In simulation, the used substrate materials were stainless steel, Ti6Al4V, low carbon steel, mild steel, medium carbon steel and Inconel 718. Based on repairing or improvement of surface properties, the used cladding materials were stainless steel, Ti6Al4V, H13 tool steel, stellite 6, TiC, WC, cobalt based alloy, aluminium based alloy and Inconel 718 [23,24,41,54,62,71,72,81,82,84,88,107]. The materials used in experimental works to improve surface properties and repairing are listed in Table 2.3. In experiments, Ti based and steel based alloy material are mainly used as substrate. Alloy/ceramics and combination of both material used as clad material. Additionally, the type of laser and important laser parameters are given in Table 2.3.

Table 2.3 The applied materials in the experimental work.

Author /year	Matrix material	Coating material	Application	Properties	Laser type	Laser power (W)	Scanning speed (mm/s)	Laser diameter (mm)
M. Dhanda / 2014 [123]	Ti6Al4V	Ni5Al (50 vol%) + HBN (10 vol%) + B ₄ C (20 vol%) + SiC (20 vol%)	Aerospace, automobile and chemical industries	Hardness and wear resistance	Ytterbium Fibre Laser (YLR-2000)	1800	34	3
H. C. Li /2015 [124]	Ti6Al4V	CaSiO ₃ , Y ₂ O ₃ and CeO ₂	Load-bearing and biocompatible	Hardness and wear resistance	a cross-flow CO ₂ laser	500	5	3
M. R. Fernández /2015 [125]	NiCrBSi	WC	High temperatures application,	Tribological improvement	CO ₂ laser	1750	200	
S. D. Sun /2014 [126]	AISI 4340 steel	Aer Met 100 steel	Aircraft structure, particularly in critical applications such as under carriages.	Fatigue behaviour	Nd:YA Glaser	1250	1000	2.5 mm

J. N. Li /2013 [127]	TA15alloy	Mainly consisted of TiAl, CoTi, CoSb intermetallics, TiC, TiB ₂ , TiB and the amorphous phases		Hardness and toughness	CO ₂ laser	1000	3-7.5	4
J. L. Chen /2015 [128]	Ti6Al4V	NiCrBSi	Aircraft	Abrasion resistance	YLS-5000 fiber laser	3000	5-20	6
X. B. Liu /2014 [129]	AISI304 austenitic stainless steel	Ni80Cr-Cr ₃ C ₂	Gas turbines, the power generation industries and aeronautical industries	Tribological properties	CO ₂ laser	1500	6	6*3
P. Kattire /2015 [130]	H13tool steel	CPM 9V steel powder	Automobile and aerospace industry	Wear and hardness	CW CO ₂ laser	4000		3
W.H. Jiang /2007 [131]	AISI 4140 steel plate	TiC/H13 tool steel	Erosion service environment	Erosion resistance	Nd:YAG	1000	12.7	1
Wenping Jiang/2001 [132]	H-13 steel substrate	TiC	die-casting	corrosion and erosion properties	CO ₂ laser	1500	42.3	0.1

J. C. Pereira /2015 [133]	austenitic stainless steel	NiCoCrAlY	Aircraft and power generation turbine	High temperature application	Nd:YAG	2000	15	4
B. A. Obadele / 2015 [134]	Ti6Al4V	TiNiZrO ₂	Biomedical applications	Corrosion	Nd:YAG laser			
J. Li / 2014 [135]	Ti6Al4V	Al ₃ Ti–TiB ₂ –(Ni-coated WC)–Al ₂ O ₃ –Y ₂ O ₃ & CeAlNi	Aerospace	Wear resistance	CO ₂ laser	800-1200	5	4
M. Doubenskaia /2015 [136]	Metal matrix (CuSn, Stellite + CuSn, stainless steel + CuSn) composite	cermet inclusions (WC–Co, WC–Co–BN)	Aerospace and automobile	Dry friction	Ytterbium fibre laser	2000	1.2-3.5	6
B. Cárcel /2014 [137]	Ti6Al4V	TiAl intermetallic (Ti 48Al2Cr2Nb)	Aeronautical and power generation industry	Tribological properties	Nd:YAG laser	500-900	600	2

J. N. Li / 2013 [138]	TA2 alloy	Fe ₃ Al–B ₄ C–TiN	Aeronautical industries	Toughness and stiffness	CO ₂ laser	1000	3-7.5	4
D. I. Adebisi / 2015 [139]	Ti6Al4V	Mo + Zr + Stellite 6	Automobile, aerospace and aeronautical industry	Hardness and wear resistance	Nd:YAG laser	400	1.4	4
F. Weng / 2015 [140]	Ti6Al4V	TiN	Automobile industries	Wear resistance	CO ₂ laser	1500		
J. N. Li / 2014 [141]	Ti6Al4V	Co–Ti–B ₄ C–Zn–Y ₂ O ₃	Aeronautical industry	Fatigue and wear resistance	CO ₂ laser	1100	3-7.5	4
Y.Lin / 2015 [142]	Ti6Al4V	TiB ₂ /NiTi	Aeronautical industry	Fracture toughness				
X. H. Wang / 2013 [143]	4Cr14Ni14NW2Mo heat-resisting steel	Ni-based WC	Aerospace industry	Hardness and wear resistance	CO ₂ laser	2200	4.5-5	4

J. Lambarri / 2013 [144]	Inconel718	-	Aeronautic components	Hardness	Nd:YAG laser	2200		2.1
A. Mthisi /2017 [145]	Ti6Al4V	Ti-Al ₂ O ₃	biomedical application	Tribological properties and delayed bioactivity	Nd:YAG laser	900	0.01-0.013	2
R.L. Sun/ 2009 [146]	Ti6Al4V	TiC/NiCrBSi	Aerospace industry	Wear resistance	CO ₂ laser	4000	8	6
M. Lua/ 2018 [147]	Ti6Al4V	TiO ₂	aerospace, automotive, biomedical and marine industries	Tribological properties and delayed bioactivity	fibre coupled diode laser	50-300	300-600	1.2

2.5 The relevance of laser cladding processes in additive manufacturing

Additive manufacturing is a process of adding metal/ceramic/polymer materials layer by layer to produce a three dimensional object. American Society for Testing and Materials (ASTM) classified this process into seven categories such as binder jetting, material extrusion, material jetting, sheet lamination, vat photopolymerization, powder bed fusion and direct energy deposition based on materials and machine technology [148,149]. The categories of additive manufacturing technology are shown in Fig. 2.6 and explained chronologically.

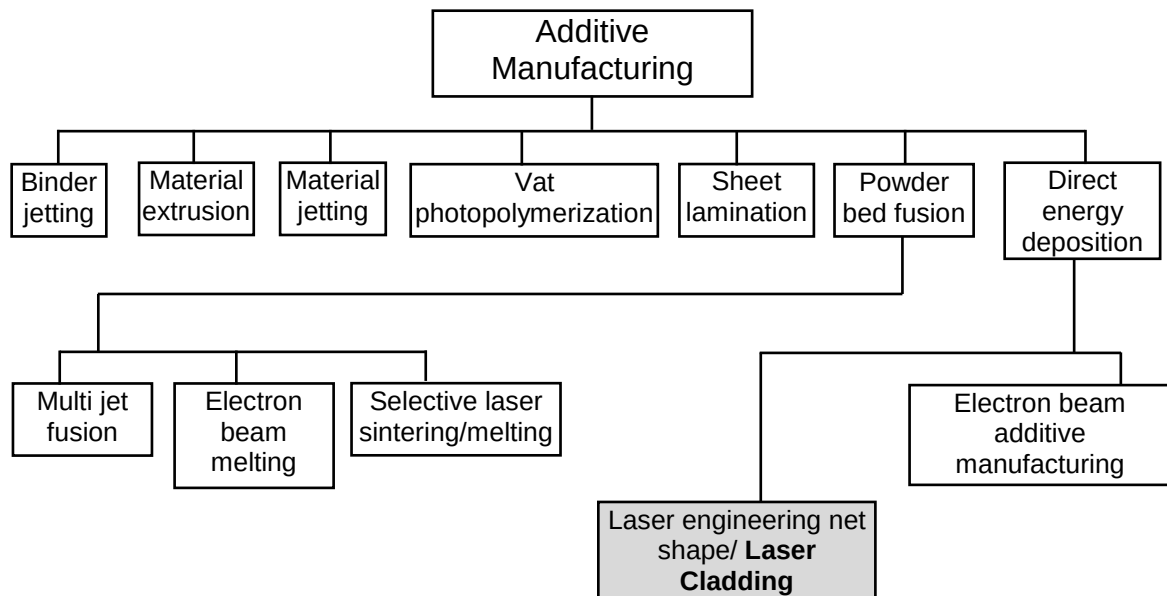


Fig. 2.6 The categories of additive manufacturing technology based on materials and machine technology [148,149].

In binder jetting, a thin layer of powder bed (polymer/metal/ceramic) is formed on the build platform [150]. Then a liquid binding agent is applied onto selected areas to create the bond between particles in that area. After finishing the first layer, build platform goes down to a defined height. After that, second layer of powders is spread on the build platform and binding agent is applied to create bond among particles.

These steps keep repeated until the final/green part is achieved. Then the green part is separated from the loose powders followed by curing, debinding and sintering. In material extrusion, molten or viscous materials (thermoplastic polymers, particulate composites, highly-filled polymers (HP) with metals or ceramics) are extruded through a nozzle/orifice to deposit stacked layers and subsequently a three-dimensional structure [151]. In material jetting technique, the droplets of liquid photosensitive material (photopolymer) are selectively deposited and solidified under ultraviolet (UV) light in successive layers [152]. In vat photopolymerization, a slurry is prepared by mixing powder materials (metal/ceramic) and photopolymer resin [153]. Then slurry is fed into the vat and the build plate is mounted in the vat. Next, a UV light is used to harden the slurry on the build plate selectively. After finishing first layer, build plate goes down to a defined height. These steps keep repeated until the final/green part is attained. Then excess slurry is removed and the green part is separated from the build part followed by debinding and sintering. In sheet lamination process, metal/composite sheet is placed on the cutting bed. A laser source is used to cut the material in a desired shape [154]. Then bonding between sheets is done by tape bonding/adhesive bonding/tagging based on component and applications. Finally, trimming of the product is done if required. In powder bed fusion process, a thin layer of powder bed is formed on the build platform [155]. Then a focused thermal energy (laser/electron beam) is applied onto selected areas to sinter or melt/fuse powders. After that, second layer of powders is spread on the build platform and focused thermal energy is applied to create bond among particles. These steps keep repeated until the final component is achieved. Finally, loose powders are removed during post processing (machining, heat treatment). In direct energy deposition process, a focused thermal energy

(laser/electron beam) is applied to melt the desired powder/wire material (metal/ceramics) which is conveyed by a nozzle and, finally deposits on an existing component for repair, coating, near net shape applications [156]. Similarly, Laser Cladding process use focused laser heat source to melt powder/wire cladding material which is deposited in the melt pool of substrate material. Both processes have similar process steps such as transportation of powder (clad materials) through nozzle, melting powder particles using focused laser heat source and, finally depositing molten clad materials on the exiting substrate/component. Therefore, Laser Cladding has a significant relevance to laser additive manufacturing.

In Laser Cladding process, several empirical-statistical, analytical and numerical models have been developed. These models are mainly used to predict geometries of clad, properties of clad, powder flow history and thermal profile, which can be applied in direct energy deposition process of additive manufacturing. The used method, process parameters and outcome of these models have been given in Fig. 2.7.

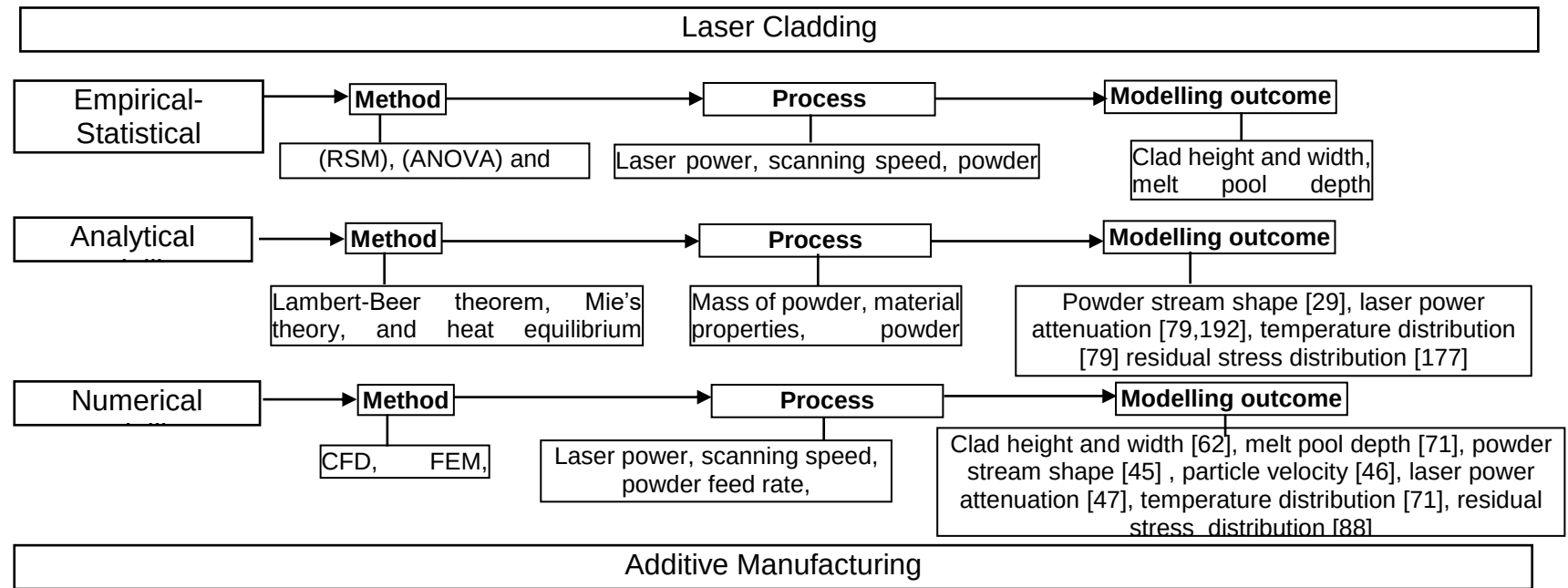


Fig. 2.7 Available models of the Laser Cladding process can be applied for additive manufacturing.

2.6 Research gap and future outlook

In this chapter, discretized numerical models of three stages of the Laser Cladding process have been summarized. Finite volume method has been mostly used to solve powder flow dynamics and fluid flow in melt pool, whereas, finite element method has been chosen to solve heat transfer and clad properties. Discretised models in all stages can be used to optimize the process parameters and explain the process physics as evident from their experimental validation. However, a single model considering all stages and process parameters is still a complex procedure and far from the real status.

In comparison to large numbers of models pertaining to powder flow dynamics and melt pool stage, modelling in clad section is still limited. We need more robust models to predict various clad properties like hardness, residual stresses, wear resistance, phase transformation, microstructural evaluations etc. The modelling of post processes such as heat treatment, machining are needed to be explored in detail. Co-axial powder system is most widely investigated and attracted by industries for the final properties of the clad. However, the process is expensive as it requires additional process steps. There have been few modelling works reported on preplaced powder system but modelling of remaining two feeding systems are still in nascent stage. There has been a good progress in numerical modelling of Laser cladding process in the last decade, but few essential challenges have to be overcome before it can be fully adopted by other advanced manufacturing techniques such as laser based additive manufacturing.

LC process offers use of a wide range of materials for coating, repairing, tooling, and rapid prototyping. Iron based alloy, titanium based alloy, cobalt based alloy, nickel based alloy, aluminium alloy, carbide, oxide, and nitride are already being

used as cladding materials in industries [1]. Currently, bioactive glass is being used for biocompatibility of medical components [120]. High entropy alloy is used for oxidation and corrosion resistance [157]. Furthermore, deposition of composite coating (ceramic embedded metal matrix) is a recent trend to get high hardness and corrosion resistance using LC process. Therefore, this process has the capability to use a wide range of materials over conventional processes. Though this process has the capability to use of a wide range of materials, different material has different flow behaviour. Therefore, there is a high requirement to develop material feeding system for different type of materials. Additionally, the interaction between materials and laser (absorption, reflection and transmission) is a critical issue and not fully understood yet. The absorption of materials depends on the material properties and wavelength of laser. So, the research on materials properties, it's flow behaviour and it's interaction with laser will take place an important part in future research work.

Initially, LC process has been used to deposit cladding materials in millimetre level for coating or repairing in a single go. Recently, deposition of nano level coating (especially for particulate reinforced metal matrix composites) from nano sized powder is more prioritised as it provides outstanding ductility and fracture toughness compare to conventional micro-particulate reinforced metal matrix composites [158]. In order to achieve superior mechanical properties in the nano level coating, intensive research is going on using this process. So, this process is capable of producing coating with fine micro-structure from nanometre to millimetre level for metal, ceramic and composite materials.

Both automated and manual laser cladding machines are available in the market. In the manual laser cladding machine, power setting, focusing distance, scanning

speed, feeding of cladding materials, speed of cladding materials are set manually. This system takes a continuous attention of technical personnel to achieve good quality clad. Recently, automated refill of cladding materials and compact laser system are available. This system is capable to change diameter of laser beam and auto focus of laser system during cladding. However, easy transfer of laser beam to the treated zone, homogenous laser beam, developed sensor for tracking geometry of clad and solidification rate, in-depth knowledge on the behaviour of powders are under research in order to achieve fully automated system and high quality clad [159].

Conventional coating methods (arc welding and thermal spraying) have many drawbacks such as low desired outputs, difficulty in installation, high operational costs, requirement of large volume of heat and additional corrective machining. Thus, the operational costs and production time for these processes increased. However, the use of laser with focused and high power provides minimal design error, less production time and increased the efficiency of the LC process [160].

The goal of developing hybrid technology is to improve their individual advantages and minimize challenges. The development of hybrid technology is in the limelight in order to achieve high deposition rate, defect free and better mechanical properties of the components. For example, the laser induction hybrid cladding or Laser Cladding with induction preheating not only increases the laser energy efficiency (upto 64%), also produce crack free clad [161]. Furthermore, addition of ultrasonic vibration during cladding can increase micro hardness in the clad, as it helps to refine grain and disperse the hard phase homogeneity in the clad [162].

3 Conceptual model

In this chapter, a physical model of the clad and the substrate has been presented. An attempt has been taken to describe a simplified relation of temperature, stress and strain with time using the established theoretical knowledge of generation of stress and strain after thermal treatment. The simplified relation of temperature, stress and strain with time has been explained with the help of schematic diagrams. The finding of this study will help to understand the temperature, stress and strain behaviour with time in the Laser Cladding process.

3.1 Model set-up

A model of the clad and the substrate has been shown in Fig. 3.1 (a). In this figure, five points (A, B, C, D and E) along the Y axis were considered to explain the effect of temperature with time during laser cladding process using an arbitrary scale. Point A is situated on the top of the clad surface and point B is placed within the clad material. Point C is based on the interface of the clad and the substrate material. Point D and E are placed in the heated zone within the substrate material. The initial state of the material at point A, B and C were molten and become solidified during cooling. On the other hand, the material at point D and E were initially heated and cool down due to large heat sink of bulk material. Temperature was raised from room temperature to high temperature. This increment of temperature with time is called heating cycle. The cooling cycle is defined as the decrease of temperature from high temperature to room temperature with time. The variation of heating and cooling rate has been shown at various position from the top surface of the clad along the Y axis. The formation of stresses and strains of the clad sample are significantly changed with differential heating and cooling rate. The generation of stress and strain with differential heating and cooling rate has been explained for

each specified position with a one dimensional example based on linear expansion and contraction behaviour. The generation of stress due to thermal process has been explained with the established knowledge of stress generation. Fig. 3.1 (b) shows the direction of normal stress in X and Y direction.

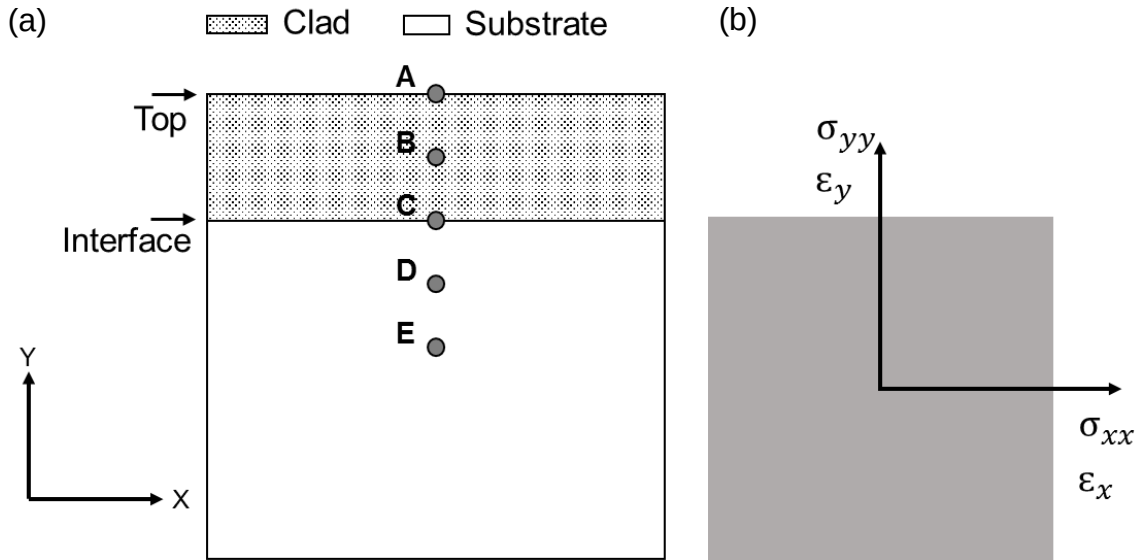


Fig. 3.1 A schematic diagram of (a) the clad and the substrate material and (b) the direction of the normal stresses (σ_{xx} , σ_{yy}) and strains (ϵ_x , ϵ_y) in a 2D element.

The classical heat conduction theory, also known as Fourier's law, was applied in order to define the temperature distribution. The initial temperature was the room temperature at the beginning of the process. The interaction of liquid metal was ignored. The heat loss due to the convection and the radiation of the laser beam was ignored. The phenomena of the chemical reaction and the stir convection were ignored. The substrate was assumed as stress free before starting the process in order to calculate the stress distribution. The bottom surface was constrained to zero displacement in both X and Y directions. The material properties of the clad and the substrate were assumed isotropic. Additionally, it was assumed that the liquid metal always had higher volume than the solid material. A non-equilibrium solidification was assumed which introduced the strain in the system [163].

3.2 Results and discussion

Fig. 3.2 represents the heating and cooling cycle of the LC process. In a co-axial system, the particles move along the laser axis get melted and dropped in the melt pool of the substrate. The heat intensity at the top of the melt pool is higher which causes a temperature gradient normal to the heat propagation [71,106]. The temperature at the end of heating cycle is indicated as T_A , T_B , T_C , T_D and T_E at points A, B, C, D and E respectively. The material at points A, B and C were in molten state. The increment of temperature at point D and E were due to the heat conduction of material. Therefore, the chronology of temperature was found $T_A > T_B > T_C > T_D > T_E$ due to temperature gradient. However, temperature difference among the points A, B and C were negligible as they all were in the molten clad zone.

The heating cycle determines the dimension of the clad and the heat affected zone [1,88]. The cooling cycle effects on the micro-structure and properties of the materials [1,88,164,165]. The heating cycle ($t_{11} - t_0$) of A, B and C point was assumed as same which was started at time t_0 and ended at time t_{11} . The heating was started later at the point D and E. The heating cycle of the point D and E were ($t_2 - t_{DS}$) and ($t_3 - t_{ES}$) respectively. t_2 , t_3 , t_{DS} and t_{ES} were ending and starting time of heating cycle of the point D and E respectively. The reasons of the cooling at the top surface is conduction, convection and radiation. The inside material cools down by only conduction or thermal gradient [88,106]. The cooling cycles were represented as ($t_A - t_{11}$), ($t_B - t_{11}$), ($t_C - t_{11}$), ($t_D - t_2$) and ($t_E - t_3$) for point A, B, C, D and E correspondingly. t_{11} was the end time of the heating cycle and the starting time of the cooling cycle of point A, B and C. t_2 and t_3 were the starting time of the cooling cycle of the point D and E respectively. The ending time of cooling cycles of point A, B, C, D and E were t_A , t_B , t_C , t_D and t_E correspondingly. The cooling cycle immediately started on the top

of the clad after removing the heat source. At the same time, the temperature of inside material was increasing due to conduction. So, cooling cycle of inside material was started later than the material around the top surface. The chronology of cooling cycle was $(t_E - t_3) > (t_D - t_2) > (t_C - t_{11}) > (t_B - t_{11}) > (t_A - t_{11})$ [106].

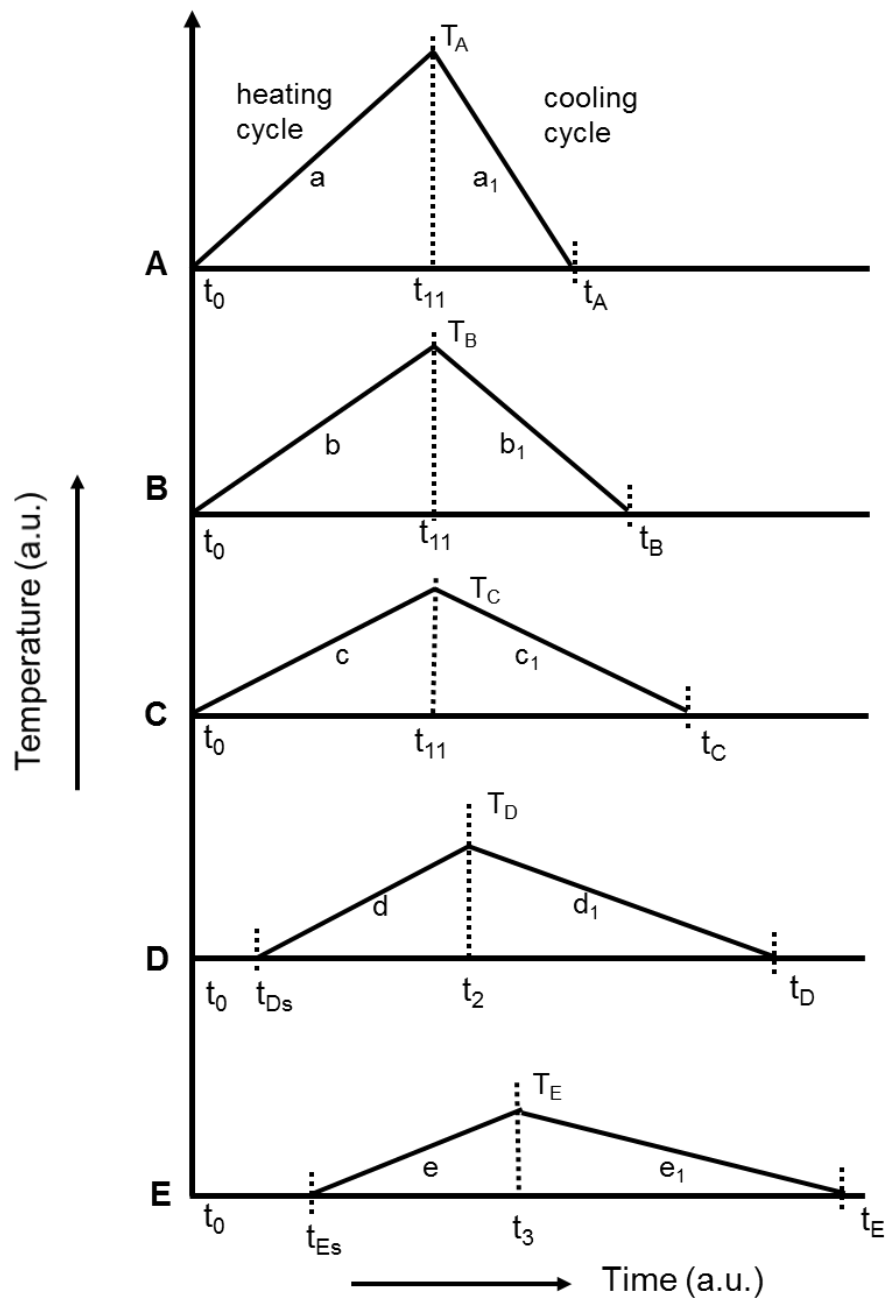


Fig. 3.2 The transient heating and cooling cycle during the thermal process.

The heating and cooling rates are the critical parameters which controls material properties [10,88]. The generation of the differential and uneven heating and cooling rate depend on the heat source, the time of heating, thermal gradients, environment temperature and material properties. The heating rates of the point A, B, C, D and E were defined as a, b, c, d and e respectively. The intensity of heat flux on the top surface was higher than the inside material. Therefore, the chronology of heating rate was $a > b > c > d > e$. The cooling rate of the point A, B, C, D and E were symbolized as a_1 , b_1 , c_1 , d_1 and e_1 respectively. The thermal gradient depends on the temperature and the position. The top surface is having the highest temperature. So, the thermal gradient at top the surface at point A was highest which causes higher cooling rate. Same as point D, the cooling rate was slower than point A as the thermal gradient was lower. The chronology of cooling rate was $a_1 > b_1 > c_1 > d_1 > e_1$.

In the molten state, liquid metal usually has higher volume that solid state. When it solidifies, material wants to come back to its original volume or equilibrium state. The non-equilibrium transformation does not allow material to come back to its original position. The initial reason of the non-equilibrium transformation is high and uneven heating rate. Another reason is the differential thermal gradient. Furthermore, the metallurgical bond in material causes the restrain which does not allow the contact material to come back to its initial state. This non-equilibrium process enters strain and stress in the system [12]. The formation of stress and strain during solidification, heating and cooling are explained by thermal expansion and contraction behaviour. During heating material expands. The extension phenomenon of material dimension is called expansion. The contraction is defined by the decrease of the dimension of material during cooling. The non-equilibrium

thermal expansion and contraction enters thermal, elastic and plastic strain and stress in the system. As a result, tensile and compressive strain and stress are generated.

For better understanding, a one-dimensional expansion and contraction diagram has been given in Fig. 3.3. At time t_1 , the material was in liquid phase at point A having length L_A^m which turned to be solid at time t_A having length L_A^s . The amount of contraction was $C_A (L_A^m - L_A^s)$. The material at point B and C were in same molten state, after solidification, the contraction was $C_B (L_B^m - L_B^s)$ and $C_C (L_C^m - L_C^s)$. The length at molten and solidified state were $L_B^m, L_C^m, L_B^s, L_C^s$ of point B and C respectively.

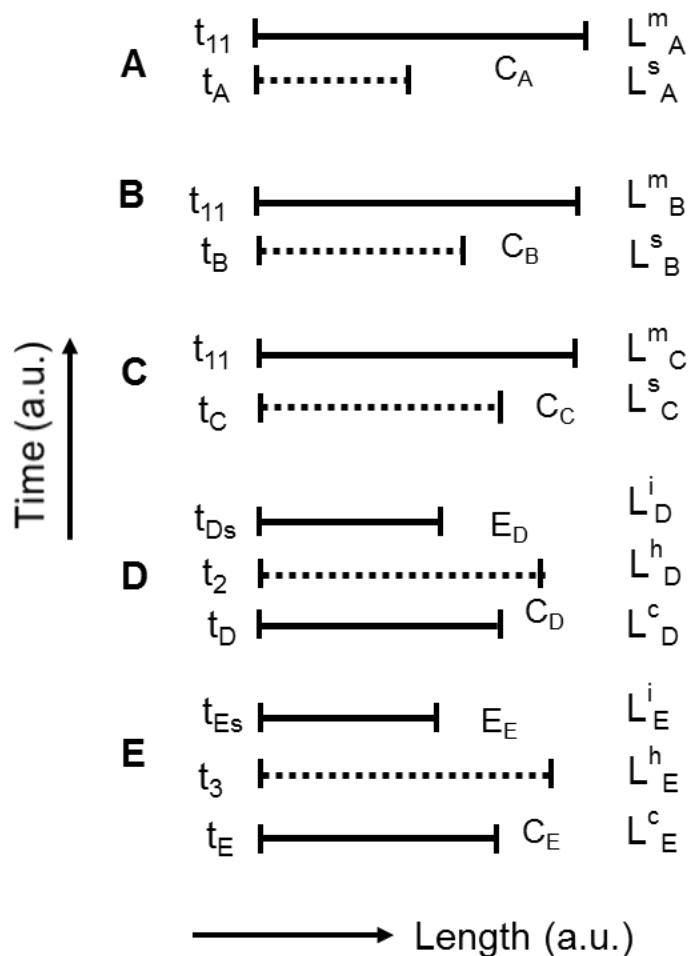


Fig. 3.3 The one-dimensional representation of the change of length with time during heating and cooling process.

The contraction chronology was $C_C < C_B < C_A$. However, the cooling rate and temperature at point A was higher than the point B and C. Also, the contraction was restricted by the surrounding materials at point C and B where above the top of the point A had no material contact. So, the contraction among A, B and C points were more or less similar. The generated strain was positive in these points and formed tensile stress [10,88]. In the heated zone (D and E point), initially, the expansion of material was denoted as $E_D (L_D^i - L_D^h)$ and $E_E (L_E^i - L_E^h)$ respectively. The length at heated and cooled state were $L_D^h, L_E^h, L_D^i, L_E^i$ of point D and E respectively. The expansion of material at point D was higher than the point E due to relatively high temperature and high cooling rate. This behaviour of material at these point formed negative strain and compressive stress. During cooling, the contraction at point D and E were $C_D (L_D^h - L_D^c)$ and $C_E (L_E^h - L_E^c)$ where $C_D < C_E$. Because, the thermal gradient and cooling rate at point E is lower than at point D. During cooling a transition happened from negative strain to positive strain.

The strain (thermal, elastic and plastic) generates in the process due to thermal treatment [12]. The generation of tensile strain at point A, B and C are denoted as St_A, St_B and St_C respectively shown in Fig. 3.4. The quantity of tensile strain was similar at A, B and C points. The compressive and tensile strain were generated at point D and E denoted as $-St_D$ and $+St_D, -St_E$ and $+St_E$ respectively.

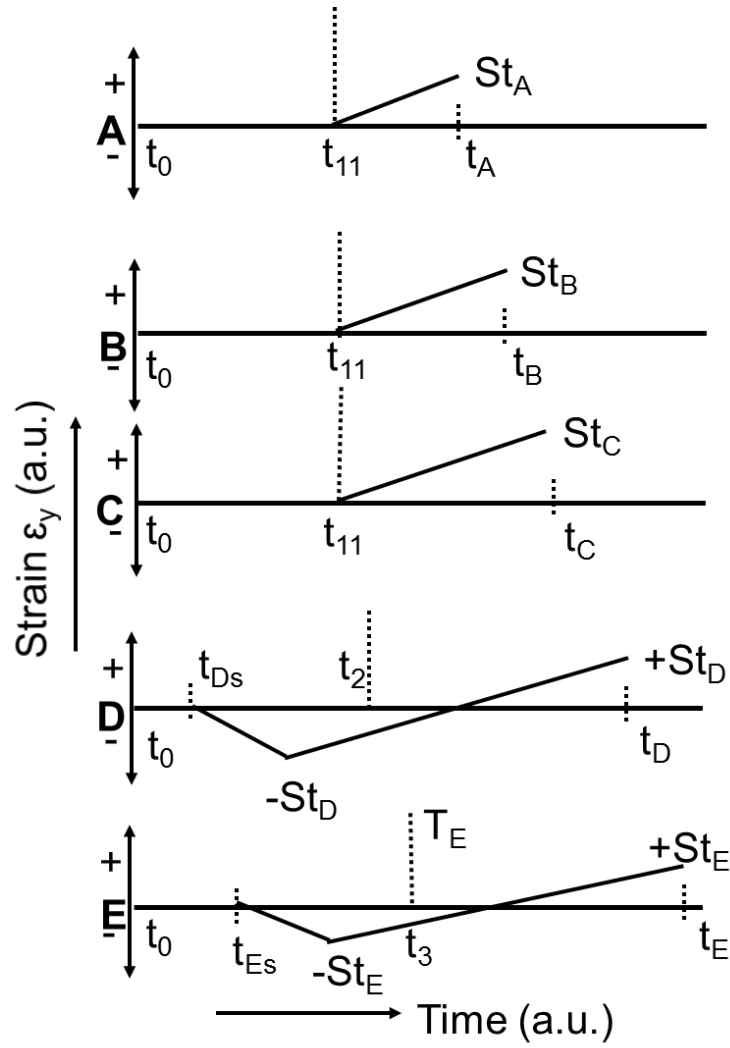


Fig. 3.4 Schematic diagrams of strain-time of the Laser Cladding process.

The generation of stress with time is presented in Fig. 3.5. During solidification of the molten zone, the generated tensile stress of points A, B and C are denoted as TS_A , TS_B and TS_C respectively. Above the top surface, there was no material. The contraction was easier at point A than the inside material. However, higher cooling rate at point A restricted the contraction, and generated tensile stress. The additional constrain was restrain of material, added during the contraction of material in B and C point. The material inside of clad zone conceived relatively higher stress [28,88,164]. However, the tensile stresses at A, B and C points had negligible difference.

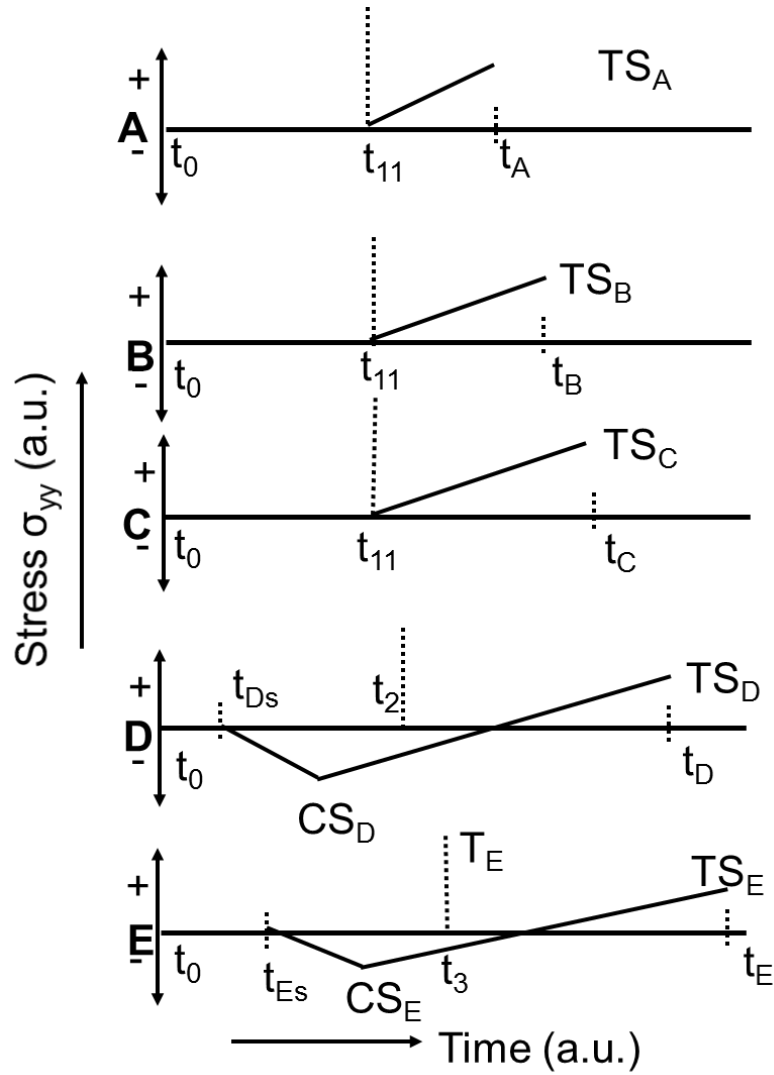


Fig. 3.5 Schematic diagrams of stress-time of the Laser Cladding process. The heated zone tries to expand against the cold elastic material. The compressive stress is generated at points D and E during heating which are denoted as CS_D and CS_E respectively. CS_D is greater than CS_E due to the higher thermal gradient at point D. During cooling, the material in the heated zone shrinks to the volume at the room temperature. However, due to the restrain of surrounding materials, the differential cooling rate and temperature difference in the heated material do not allow them to come back to the original volume. As a consequence, the compressive stress is turned into tensile stress where TS_D was greater than TS_E [12,164].

3.3 Conclusion

A simple conceptual model of Laser Cladding process has been presented to discuss the effect of temperature on strain and stress in different location during the Laser Cladding process. The magnitude of temperature, heating rate and cooling rate in the clad material were higher than in the substrate material. From the clad top surface to substrate at near interface, tensile strain and stresses were found. During heating, compressive stress was formed near the interface of substrate which turned in to tensile stress at the end of cooling.

4 The analytical model

This chapter focuses on to find out key reasons of formation of tensile residual stresses in dissimilar clad and substrate materials. In order to predict the tensile residual stress, one dimensional analytical model has been adopted. The thermal strain (multiplication of thermal expansion coefficient and temperature change) and Young's modulus are found as key reasons of formation residual stresses. Additionally, the investigation of preheating temperature of the substrate showed the reduction of residual stress with increasing the preheating temperature of the substrate.

4.1 Model set-up

H13 steel and Ti6Al4V were used as a substrate material. Four cladding materials (Al_2O_3 , TiC, TiO_2 and ZrO_2) were used on the H13 steel substrate and a range of preheating temperature of the substrate, from 300 K to 1200 K, was investigated. For Ti6Al4V substrate, six cladding materials (Al_2O_3 , TiC, TiO_2 , ZrO_2 , SiC and TiN) were used and, 300 K to 1000 K was the range of preheating temperature of the substrate. The chosen cladding materials were taken as they are widely used in coating applications. The pre heating temperature range of substrate has been selected based on the phase change of substrate materials. The material properties can be found in Table 4.1 and Table 4.2.

Table 4.1 The material properties of H13 steel and cladding materials.

Materials	Thermal expansion coefficient (K⁻¹)× 10⁻⁶	Young's Modulus (GPa)	Melting temperature (K)	Height (m)
H13 tool steel ⁺ [88]	10.50	210	1727	0.005 [*]
Al ₂ O ₃ ⁺⁺ [166]	5.40	380	2345	0.001 ^{**}
TiC ⁺⁺ [167]	7.70	315	3340	0.001 ^{**}
TiO ₂ ⁺⁺ [168]	11.80	288	2123	0.001 ^{**}
ZrO ₂ ⁺⁺ [169]	12.20	250	2522	0.001 ^{**}

⁺ Substrate material and ⁺⁺ Cladding materials, ^{*} h_s and ^{**} h

Table 4.2 The material properties of Ti6Al4V and cladding materials.

Materials	Thermal expansion coefficient (K⁻¹)× 10⁻⁶	Young's Modulus (GPa)	Melting temperature (K)	Height (m)
Ti6Al4V ⁺ [170]	9.1	140		0.005 [*]
Al ₂ O ₃ ⁺⁺ [166]	5.40	380	2345	0.0005 ^{**}
TiC ⁺⁺ [167]	7.70	315	3340	0.0005 ^{**}
TiO ₂ ⁺⁺ [168]	11.80	288	2123	0.0005 ^{**}
ZrO ₂ ⁺⁺ [169]	12.20	250	2522	0.0005 ^{**}
SiC ⁺⁺ [171]	11	130	1955	0.0005 ^{**}
TiN ⁺⁺ [172]	9.4	600	3223	0.0005 ^{**}

⁺ Substrate material and ⁺⁺ Cladding materials, ^{*} h_s and ^{**} h_c

A simplified model was adopted to calculate the residual stress as shown in Fig. 4.1 [163,164]. In this process, the Eq. 4.1 was used by considering the elastic and the thermal strain.

$$\sigma_c = \frac{h_s E_s E_c [\alpha_c (T_{mc} - T_r) - \alpha_s (T_0 - T_r)]}{h_s E_s + h_c E_c} \dots \dots \dots (4.1)$$

where, σ_c is the normal residual stress of clad. α , E and h are defined as the thermal expansion coefficient, Young's Modulus and the thickness. The subscript c and s represents the clad and the substrate material respectively. T_r , T_0 and T_{mc} are the room temperature, preheating temperature of the substrate and melting temperature of the clad respectively. The complete derivation of Eq. 4.1 has been given in appendix B.

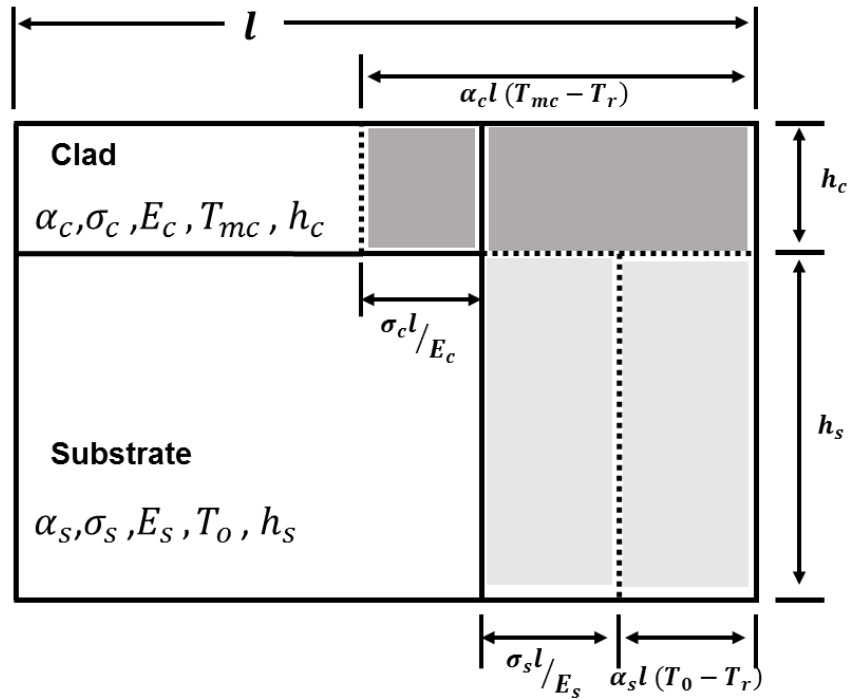


Fig. 4.1 The geometry of residual stress model based on thermos-elastic mechanics [164].

4.2 Results and discussion

4.2.1 H13 steel substrate

Four cladding materials (Al_2O_3 , TiC, TiO_2 , ZrO_2) on the H13 tool steel substrate and a range of preheating temperature of the substrate, from 300 K to 1200 K, were investigated. Fig. 4.2 shows the distribution of predicted tensile residual stresses for four cladding materials (Al_2O_3 , TiC, TiO_2 , ZrO_2) on the H13 steel substrate for a range of preheating temperature (300 K to 1200 K) of the substrate. TiC cladding material generated the maximum tensile residual stress below 900 K preheating temperature of the substrate while ZrO_2 cladding material experienced the maximum tensile residual stress above 900 K preheating temperature of the substrate, see Fig. 4.2. The minimum residual stress was formed for Al_2O_3 cladding material.

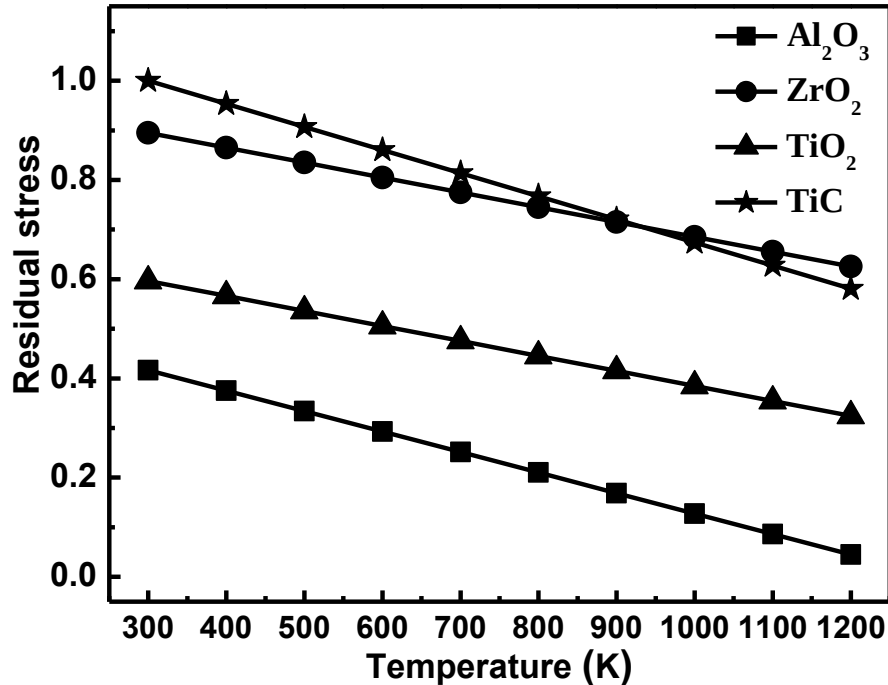


Fig. 4.2 Distribution of the normalized residual stress with preheating temperature of H13 steel substrate for four cladding materials.

The predicted residual stress of four cladding materials at 300 K and at 1200 K preheating temperature of the substrate are shown in Fig. 4.3 (a) and Fig. 4.3 (b) respectively. It was observed that with increasing the preheating temperature of the substrate material, the generated residual stresses were decreasing. To understand the variation of residual stresses for different material systems and preheating temperature, the mismatch of thermal strain between clad and the substrate and Young's modulus have been analysed.

The mismatch of thermal strain (multiplication of thermal expansion coefficient and temperature change), $\alpha_c(T_{mc} - T_r) - \alpha_s(T_0 - T_r)$ in Eq. 3, between the clad and the substrate material is one of the key reasons of the formation of residual stress. The difference of the thermal strain of four cladding materials with the substrate material are shown in Fig. 4.4 (a) and Fig. 4.4 (b) at the 300 K and 1200 K preheating temperature of the substrate respectively.

ZrO₂ cladding material showed higher mismatch of thermal strain with the substrate at any preheating temperature than other clad materials, see Fig. 4.4 (a) and Fig. 4.4 (b). However, below 900 K preheating temperature of the substrate, TiC cladding material generated higher tensile residual stress than ZrO₂ cladding material. In order to clarify this issue, another material property, Young's modulus, was investigated. The Young's modulus of TiC and ZrO₂ cladding materials are 449 GPa and 380 GPa respectively. From Eq 4.1, we have taken the part related with mismatch of thermal strain and Young's modulus of clad material, $E_c[\alpha_c(T_{mc} - T_r) - \alpha_s(T_0 - T_r)]$, to explain this trend. The product of mismatch of thermal strain and Young's modulus was shown in Fig. 4.5 (a) and Fig. 4.5 (b).

Product of mismatch of thermal strain and Young's modulus of TiC at 300 K is higher than ZrO₂ while product of mismatch of thermal strain and Young's modulus of TiC is lower than ZrO₂ at 1200 K. TiC has higher Young's modulus and very small difference between mismatch of thermal strain compared to ZrO₂ at 300 K. However, mismatch of thermal strain was decreased with increasing the preheating temperature of the substrate. The degree of decrement of the mismatch of thermal strain between TiC cladding material and the substrate was higher than ZrO₂ cladding material above 900 K generating lower residual stress, though the Young's modulus of TiC is higher.

If we compare between Al₂O₃ and ZrO₂ cladding materials, the Young's modulus of Al₂O₃ (380 GPa) cladding material is higher than ZrO₂ (250 GPa) cladding material. However, ZrO₂ cladding material produced higher residual stress due to the higher mismatch of thermal strain with substrate compared to Al₂O₃.

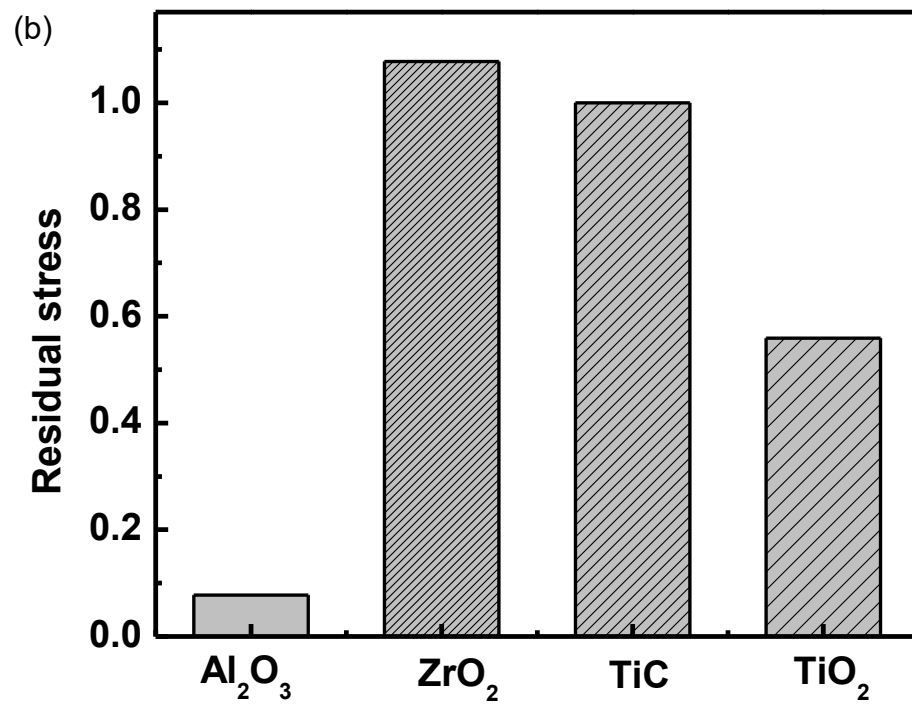
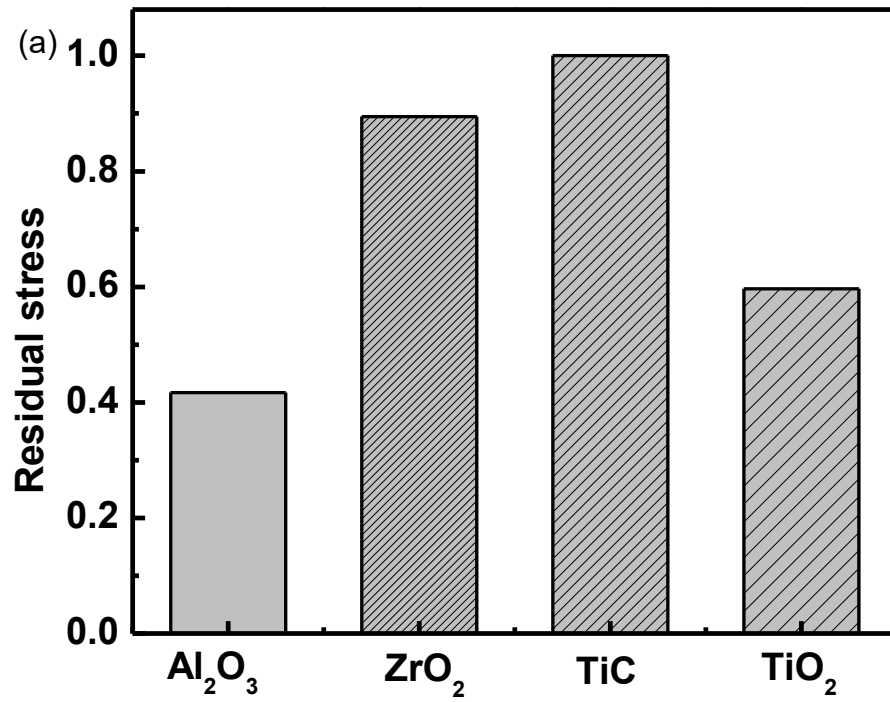


Fig. 4.3 The normalized residual stress (a) at 300 K and (b) at 1200 K preheating temperature of H13 steel substrate for four cladding materials.

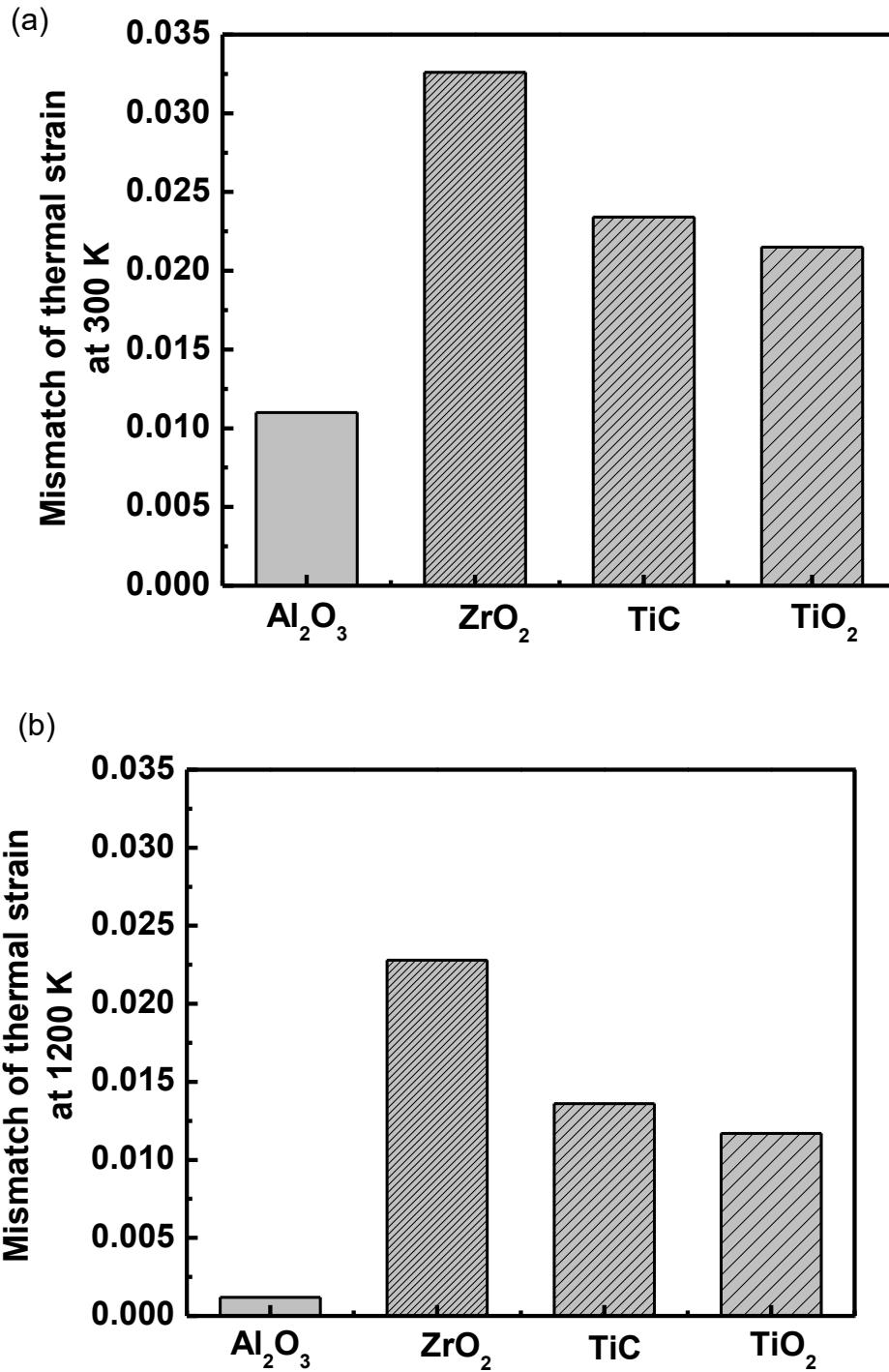


Fig. 4.4 Mismatch of thermal strain between cladding materials and the H13 steel substrate (a) at 300 K and (b) at 1200 K preheating temperature of the substrate.

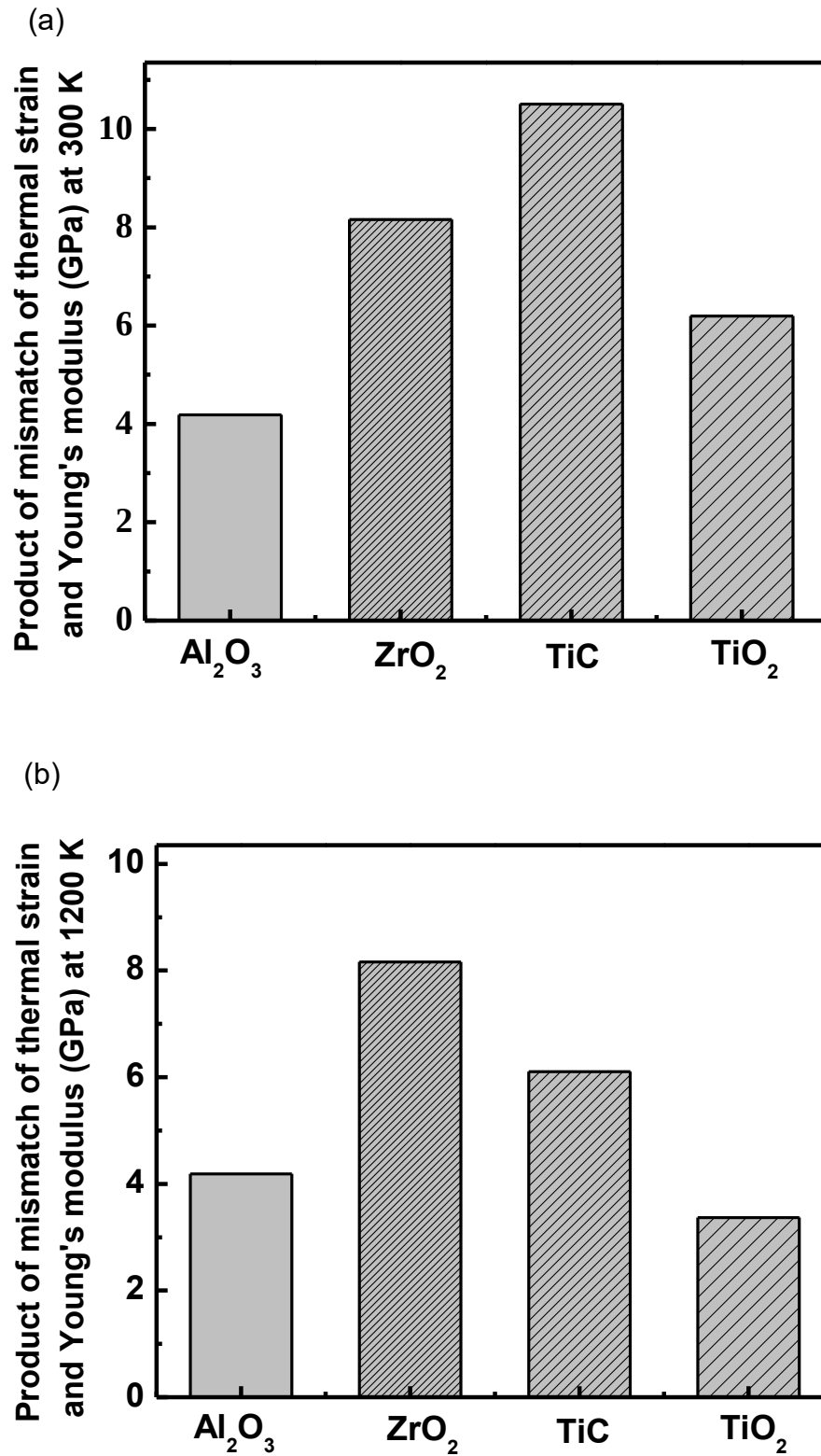


Fig. 4.5 Product of mismatch of thermal strain and Young's modulus (a) at 300 K and (b) at 1200 K preheating temperature of H13 steel substrate for four cladding materials.

4.2.2 Ti6Al4V substrate

The distribution of predicted tensile residual stresses for six cladding materials (Al_2O_3 , TiC, TiO_2 , ZrO_2 , SiC and TiN) on the Ti6Al4V substrate for a range of preheating temperature (300K to 1200K) of the substrate are shown in Fig. 4.6. TiN cladding material generated the maximum tensile residual stress. Al_2O_3 clad materials generated higher residual stress than SiC below 1000 K where at 1000 K SiC and Al_2O_3 generated almost similar residual stress.

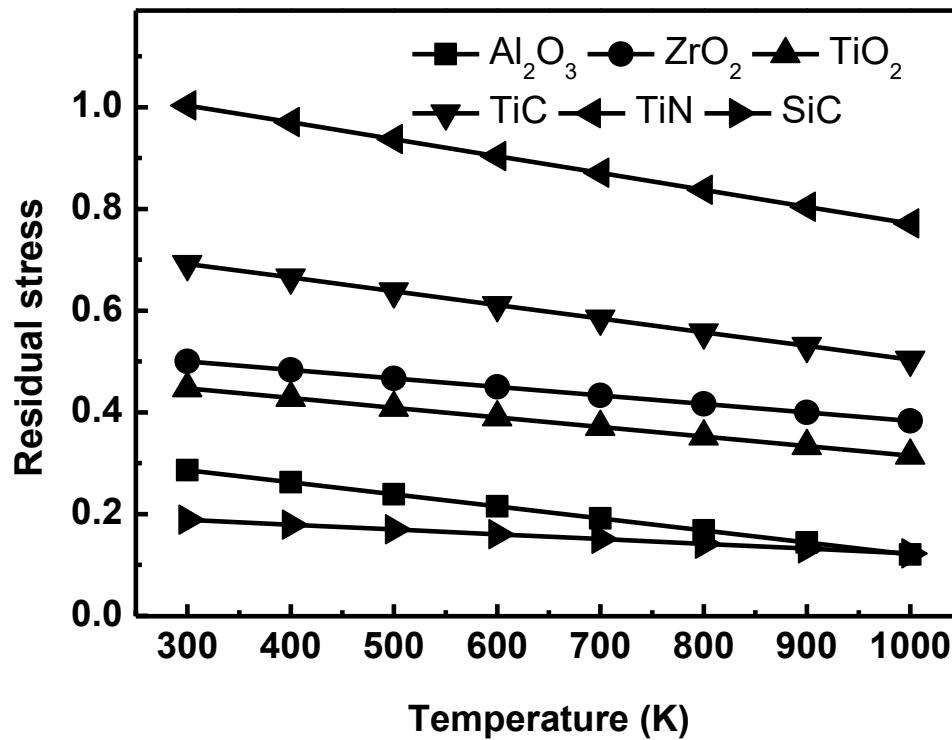


Fig. 4.6 Distribution of the normalized residual stresses with preheating temperature of Ti6Al4V substrate for six cladding materials.

The normalised predicted residual stress of six cladding materials at 300 K and at 1000 K preheating temperature of the substrate are shown in Fig. 4.7 (a) and (b) respectively. The increment of the preheating temperature of the substrate decreased residual stresses for all cladding materials. The mismatch of thermal

strain between the clad and substrate materials have been focused to understand the difference of residual stresses for different cladding material systems.

The mismatch of the thermal strain of cladding materials from the substrate material are shown in Fig. 4.8 (a) and (b) at the 300 K and 1000 K preheating temperature of the substrate respectively. At any preheating temperature of the substrate material, Al₂O₃ cladding material showed lower mismatch of thermal strain with the substrate than SiC cladding material, see Fig. 4.8 (a) and (b). However, Al₂O₃ generated higher residual stress than SiC below 1000 K preheating temperature of the substrate. The reason can be understood by analysing materials Young's modulus. The Young's modulus of SiC and Al₂O₃ cladding materials are 130 GPa and 380 GPa respectively. The part of Eq. 4.1, $E_c[\alpha_c(T_{mc} - T_r) - \alpha_s(T_0 - T_r)]$, which is related with mismatch of thermal strain and Young's modulus are taken to explain this trend. The product of mismatch of thermal strain and Young's modulus was shown in Fig. 4.9 (a) and (b).

The product of mismatch of thermal strain and Young's modulus of Al₂O₃ at 300 K is higher than SiC which causes higher residual stress in Al₂O₃. However, with increasing the preheating temperature of the substrate, mismatch of thermal strain was decreasing. At 1000 K, the degree of decrement of the mismatch of thermal strain between Al₂O₃ cladding material and the substrate was higher than SiC cladding material. As a results similar residual stresses were found in both SiC and Al₂O₃ cladding material systems, though the Young's modulus of Al₂O₃ is higher.

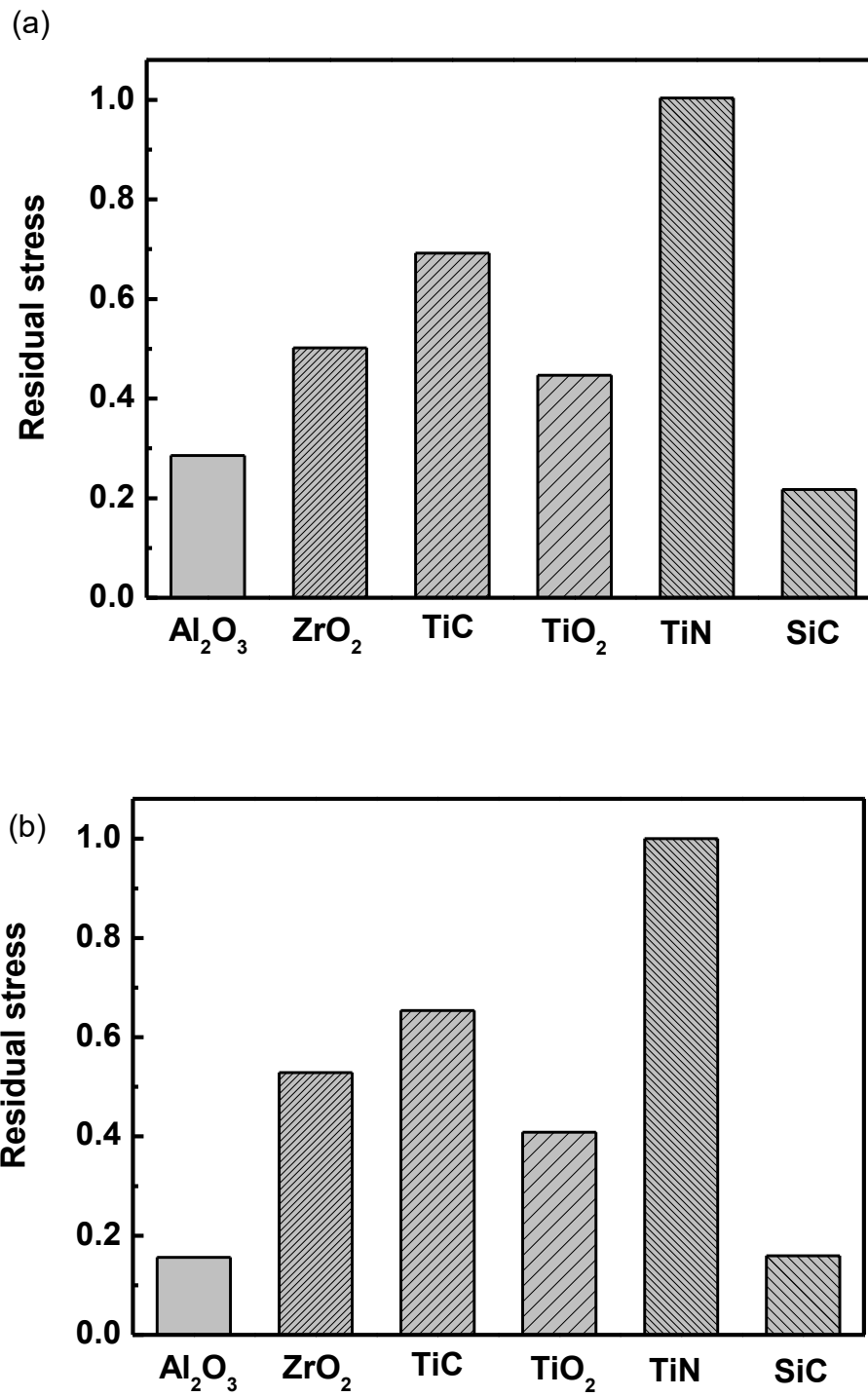


Fig. 4.7 The normalized residual stress (a) at 300 K and (b) at 1000 K preheating temperature of Ti6Al4V substrate for four cladding materials.

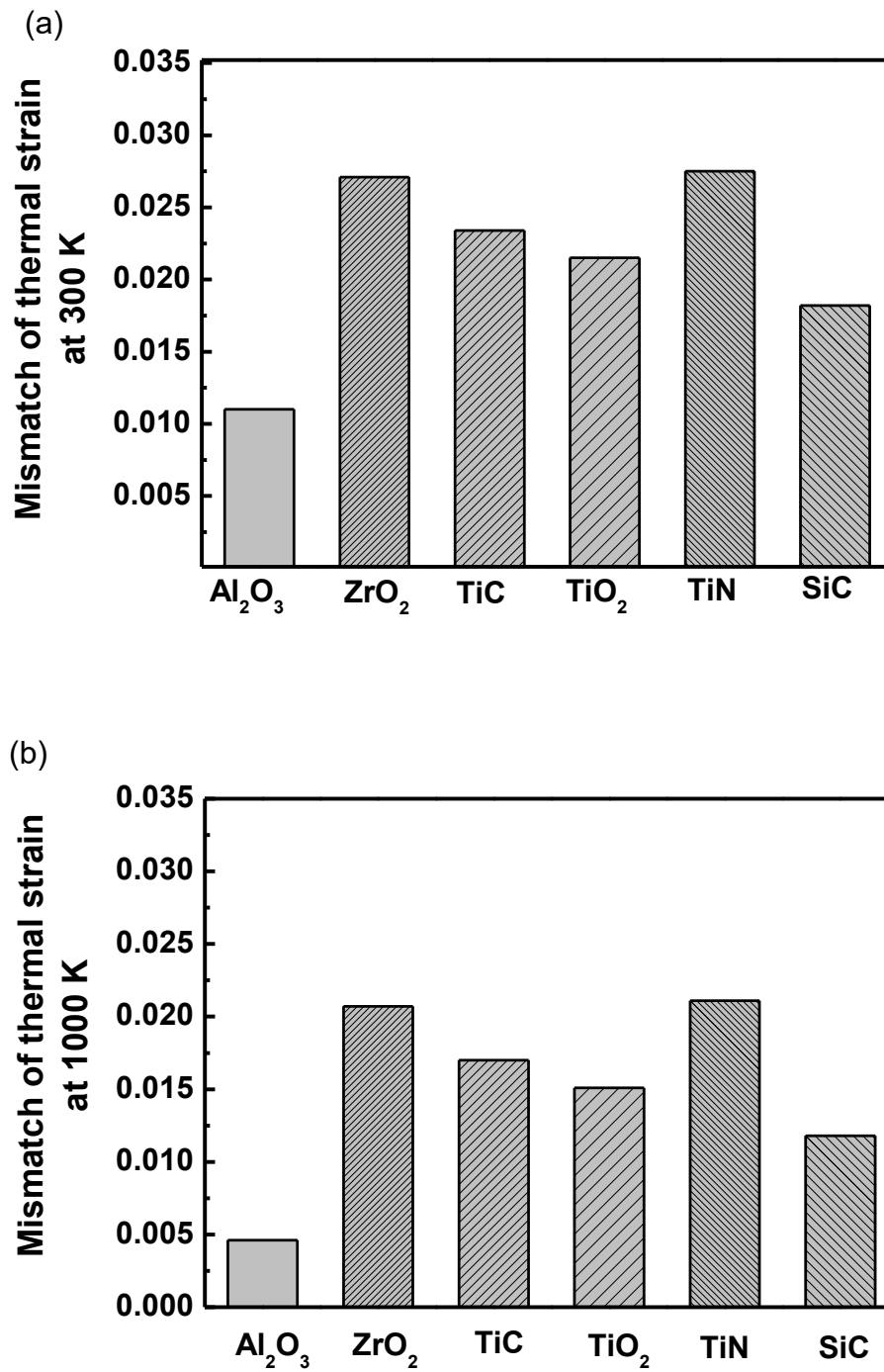
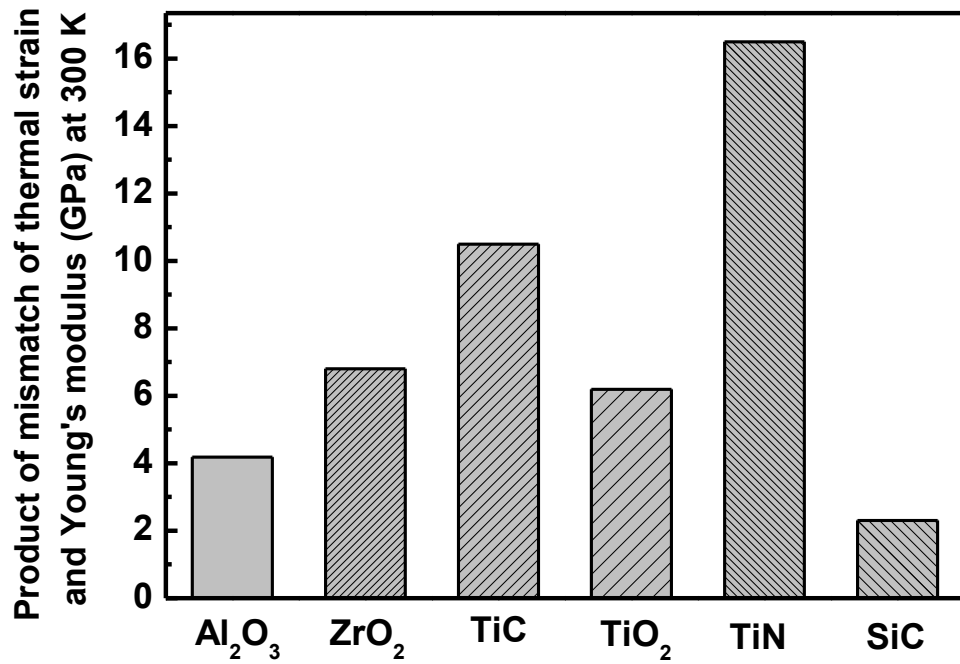


Fig. 4.8 Mismatch of thermal strain between cladding materials and Ti6Al4V substrate (a) at 300 K and (b) at 1000 K preheating temperature of the substrate.

(a)



(b)

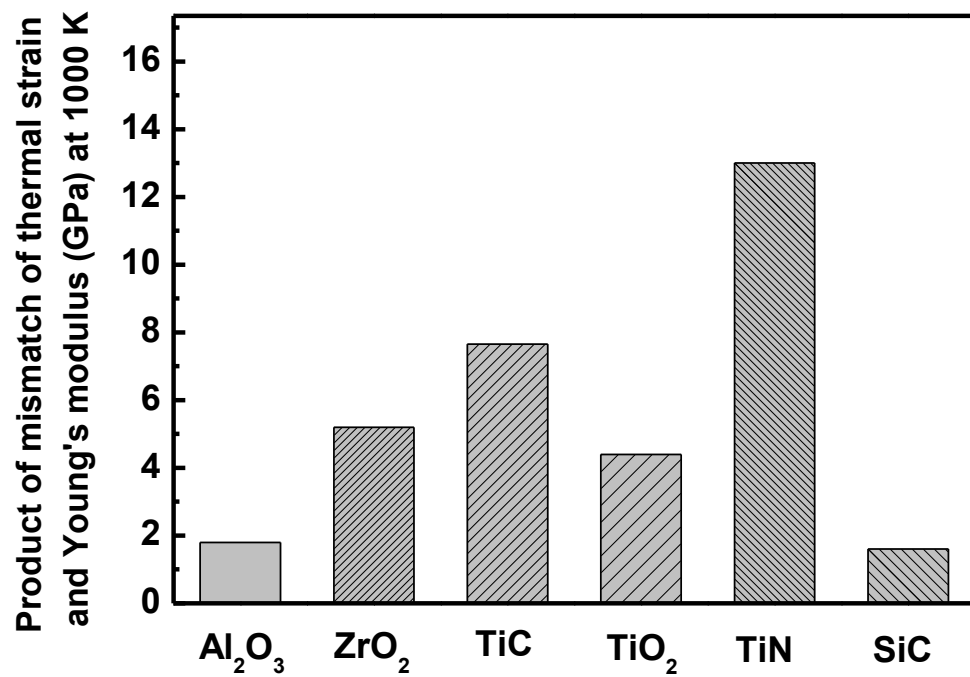


Fig. 4.9 Product of mismatch of thermal strain and Young's modulus (a) at 300 K and (b) at 1000 K preheating temperature of Ti6Al4V substrate for six cladding materials.

4.3 Conclusion

An analytical model has been used to predict and compare stresses in dissimilar clad and substrate material system with a range of preheating temperature of the substrate. Four cladding materials TiO_2 , TiC , ZrO_2 and Al_2O_3 were used on the H13 steel substrate. The minimum residual stress was found for Al_2O_3 clad on the H13 steel substrate. Below 900 K, preheating temperature of the substrate, maximum residual stress was generated in the TiC clad. The maximum residual stress formed in ZrO_2 clad above 900 K. Six cladding materials (Al_2O_3 , TiC , TiO_2 , ZrO_2 , SiC and TiN) on the Ti6Al4V substrate at a range of preheating temperature (300 K to 1200 K) of the substrate were investigated. TiN cladding material generated the maximum tensile residual stress on the Ti6Al4V substrate. Below 1000 K, Al_2O_3 generated higher residual stress than SiC and at 1000 K, SiC and Al_2O_3 generated almost same residual stress. The thermal strain and Young's modulus were found as key reasons of the generation and control of residual stresses. This analysis can be used to find a combination of materials that can generate minimum residual stress. This model is capable to include preheating temperature of the substrate and predict its effect on the distribution of the residual stress. The increment of preheating temperature of substrate decreased the residual stress.

In this model, temperature independent material properties have been used. This model is limited to use the effect of temperature dependent material properties. Moreover, this model cannot predict the generation of stresses in more than one dimension. Furthermore, this model was restricted to melting temperature of the clad material. However, in practical scenario, surface of the substrate material also reach to melting temperature by laser heat source which cannot be included here. These limitations have been removed by applying numerical method in the Laser Cladding process in next chapters.

5 2D FE model for single step heat source

In this chapter, 2D thermo-mechanical models have been developed numerically using ANSYS'18 multi-physics platform to compare generated residual stresses among different cladding materials. As a substrate material, H13 steel was used and H13 steel, Al_2O_3 and TiC were used as cladding materials. Tensile residual stresses were observed in the clad, at the interface and in the substrate near the interface in all samples. It was found that Al_2O_3 coating on H13 steel produced lower residual stress (1220 MPa) in the clad than TiC coating on H13 steel (1359 MPa). This proposed analysis offers a guideline to select the combination of clad and substrate materials having minimum residual stresses in the Laser Cladding process.

5.1 Model set up

5.1.1 Geometry and mesh

A single step 2D thermo-mechanical model of Laser Cladding has been developed using ANSYS'18 mechanical APDL multi-physics platform. For this model, the geometry of the substrate and the clad layer was adopted based on developed work by Bailey et. al [115]. The dimensions of the substrate geometry were 12 mm width and 5 mm height while the clad height and width were taken 0.786 mm and 0.169 mm respectively. The 2D geometry and mesh is given in Fig. 5.1. For meshing, transitional mapped mesh technique was applied to achieve accurate calculation of the temperature distribution and residual stresses distribution. The clad layer and part of the substrate area were meshed with finer elements as the heat/temperature distribution is mostly restricted in that area. Rest of the substrate area was gradually meshed with coarser elements by following ratios between fine and coarse element

size. This non-uniform mesh distribution helps to minimise the number of elements. The total number of elements in this model was 1337.

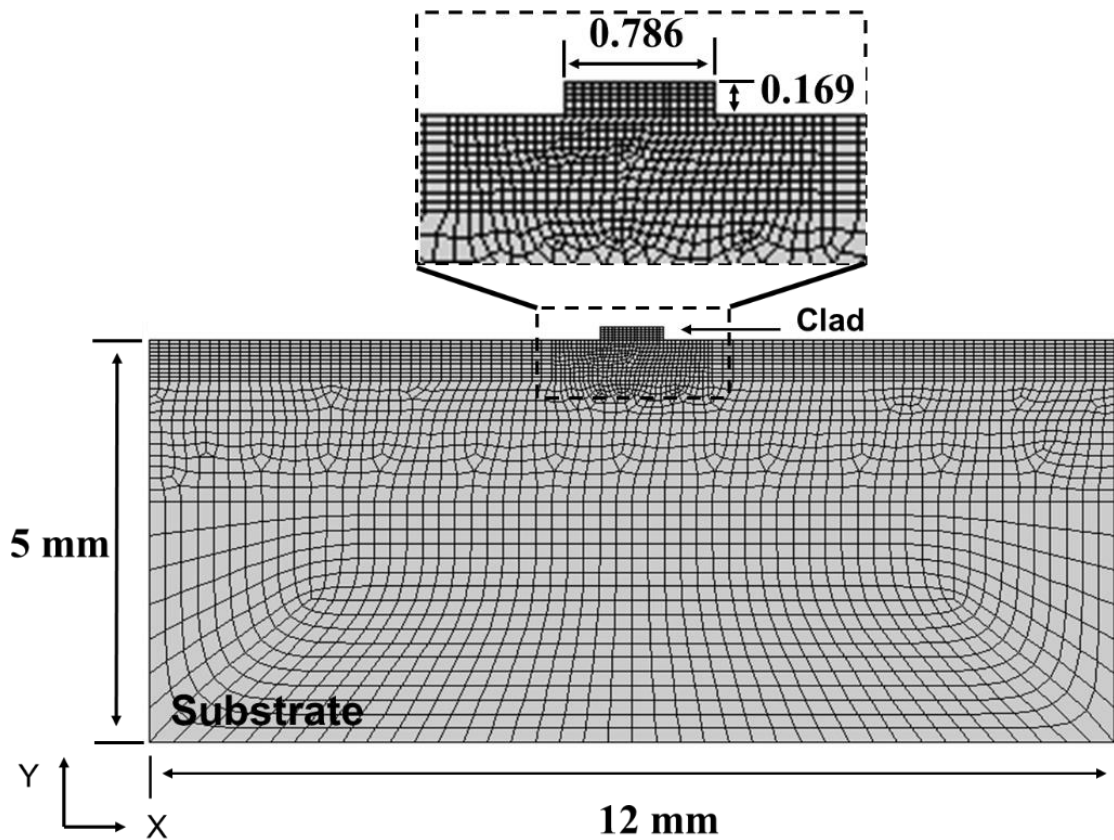


Fig. 5.1 The 2D model geometry (mm) and mesh.

For thermal analysis, “plane 55” element type was used which is a quadrilateral element having 4 nodes with a single degree of freedom, temperature. This element is widely utilised for 2D finite element thermal analysis [173]. Then, the thermal element was switched to the “plane 182” element type for conducting load transfer thermo-mechanical analysis. This is also a quadrilateral element having 4 nodes which has two degree of freedom i.e. displacement in X and Y direction. In order to predict more accurate results, the mesh convergence has been done shown in Fig. 5.2. The temperature was recorded at the interface of the clad and the substrate for different number of elements.

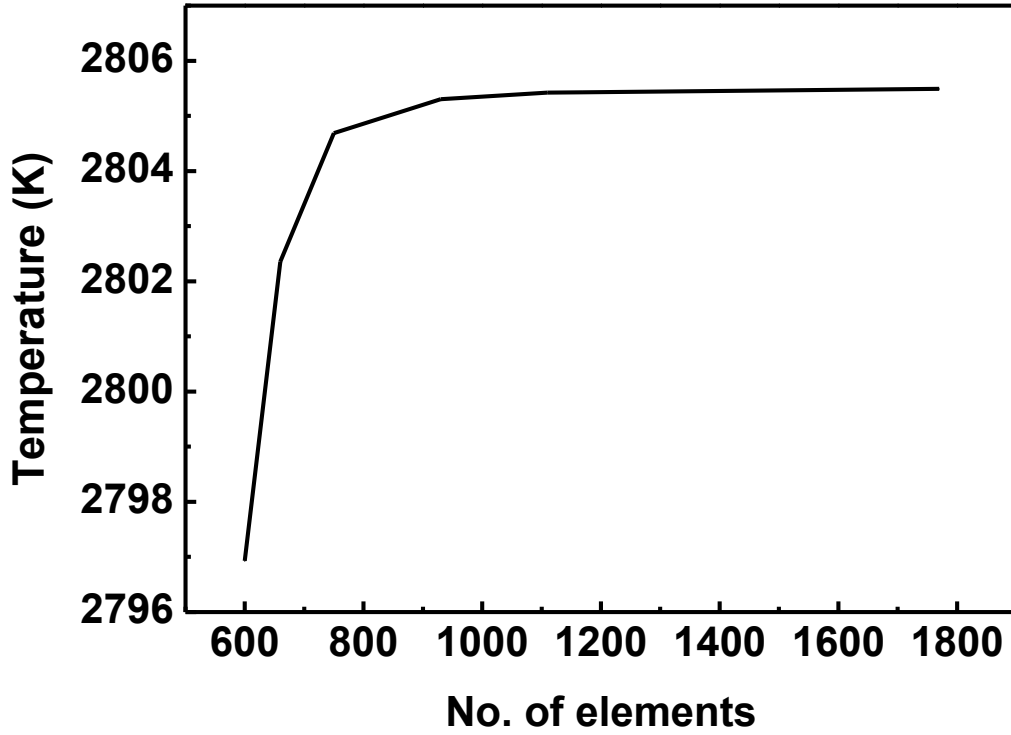


Fig. 5.2 Mesh convergence of 2D finite element model.

5.1.2 Materials and properties

For single step heat source model, H13 steel, Al_2O_3 and TiC were deposited as cladding materials on the surface of the substrate material, H13 steel. These cladding materials are chosen based on their wide use as coating materials in industries. In this work, three different clad materials samples are named as H13/H13, $\text{Al}_2\text{O}_3/\text{H13}$ and TiC/H13. The temperature independent material properties used to develop thermo-mechanical model are given in Table 5.1.

Table 5.1 Thermo-mechanical properties of H13 steel [115], Al₂O₃ [174] and TiC [167] materials.

	Property	Units	H13 steel	Al ₂ O ₃	TiC
Thermal material properties	Density	kg/m ³	7835	3980	4940
	Specific Heat	J/kg-K	658	955	781.66
	Thermal conductivity	W/m-K	28.6	38.5	30.93
	Thermal expansion coefficient	× 10 ⁻⁶ 1/K	14.5	10.9	7.7
	Melting temperature	K	1745	2369	3338
Mechanical material properties	Young's modulus	GPa	210	413	451
	Poisson's ratio	-	0.3	0.33	0.19

5.1.3 Laser parameters

For single step heat source model, heat density (W/m²) is usually applied in the clad material to predict temperature distribution. Heat density is dependent on two laser parameters: laser power and material absorptivity, see Eq. C5 in appendix C. Material absorptivity depends on the wavelength of laser. For examples, the absorptivity of H13 steel, Al₂O₃ and TiC are 0.15, 0.03 and 0.82 respectively for fiber laser (wavelength is 1.06 μm). On the other hand, the absorptivity for CO₂ laser are 0.3, 0.96 and 0.46 of H13 steel, Al₂O₃ and TiC respectively. Based on the absorptivity of materials, different level of power is required to achieve the same heat density, see Table 5.2. In this model, laser parameters (laser power and absorptivity) were adopted from the experimental data for the deposition of H13 steel powder on the surface of H13 steel substrate [115]. For H13 steel, the used laser power and absorptivity were 350 W having 0.74 mm beam diameter and 0.15

respectively. For $\text{Al}_2\text{O}_3/\text{H13}$ and $\text{TiC}/\text{H13}$ samples, laser power were optimized based on absorptivity under different wavelength lasers, given in Table 5.2.

Table 5.2 Laser process parameters for H13/H13 [115], $\text{Al}_2\text{O}_3/\text{H13}$ [175] and $\text{TiC}/\text{H13}$ [175] cladding samples. Note that in all cases the substrate is H13 tool steel.

Laser Parameters	Units	Laser type	H13 tool steel	Al_2O_3	TiC
Laser power	W	Fiber	350	1792	82
		CO_2	173	56	145
Laser travel speed	mm/s	-	14.8	14.8	14.8
Beam diameter	mm	-	0.74	0.74	0.74
Absorption coefficient	-	Fiber	0.15	0.03	0.82
		CO_2	0.3	0.96	0.46

5.2 Results and discussion

5.2.1 Thermal analysis

The temperature distribution of the 2D single step thermal model of H13/H13 cladding sample is shown in Fig. 5.3. The localised isothermal distribution of temperature contour shows that a large amount of heat input is confined into the clad, interface and small part of the substrate. It causes high temperature above the melting point of H13 steel (1745 K) and a sharp thermal gradient to the surrounding materials of the substrate. The zoomed in view of the temperature isotherm in Fig. 5.3 points out that the temperatures of the entire clad, interface and small region of the substrate lie above the melting point. This indicates that a good metallurgical bonding is established between the clad and the substrate at interface. Additionally, the corner part of clad reached very high temperature, which might evaporate during

the process. Similar temperature isotherms for $\text{Al}_2\text{O}_3/\text{H13}$ and $\text{TiC}/\text{H13}$ cladding samples can be extracted from the corresponding thermal models.

The temperature vs time graphs have been plotted in Fig. 5.4 for all three cladding samples from the thermal models. The peak temperatures for the H13/H13, $\text{Al}_2\text{O}_3/\text{H13}$ and $\text{TiC}/\text{H13}$ cladding samples were 3115 K, 3275 K and 4831 K respectively at constant beam width and laser speed. The peak temperature of all cladding samples were higher than the melting temperature of the corresponding clad materials which indicated large thermal gradients remain between clad and cold substrate. This caused sharp cooling rates in the clad which induces the residual stress in the samples. Fig. 5.4 shows that $\text{TiC}/\text{H13}$ sample achieved higher cooling rates than the other sample due to the larger temperature gradient.

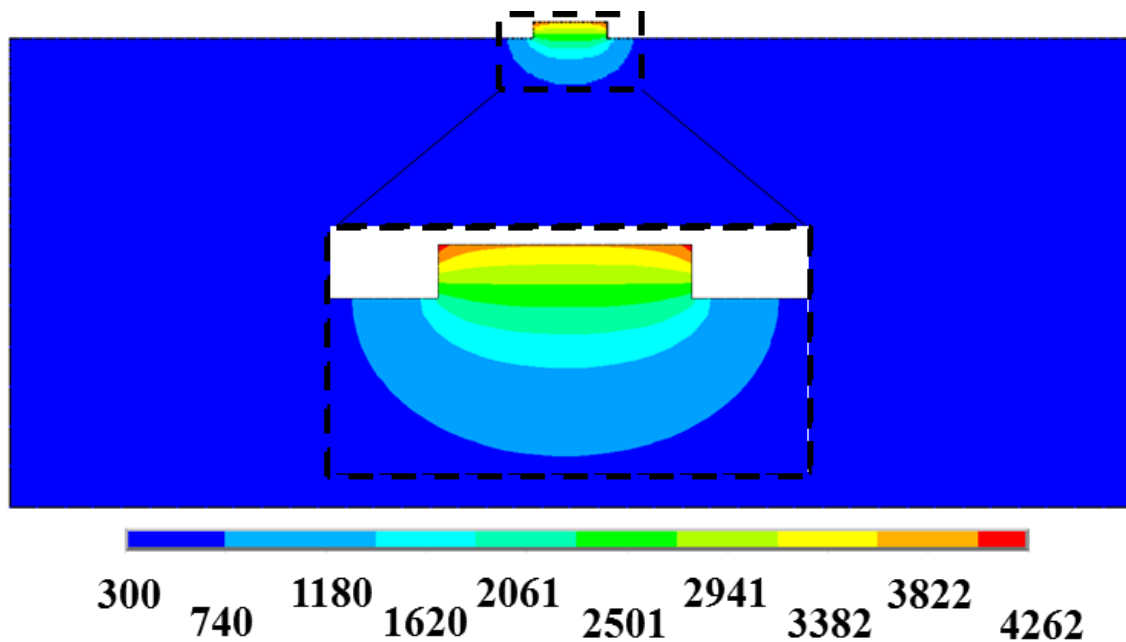


Fig. 5.3 The 2D temperature distribution (K) at 0.053 s. Power = 350 W, beam diameter = 0.74 mm and scanning speed = 14.8 mm/s.

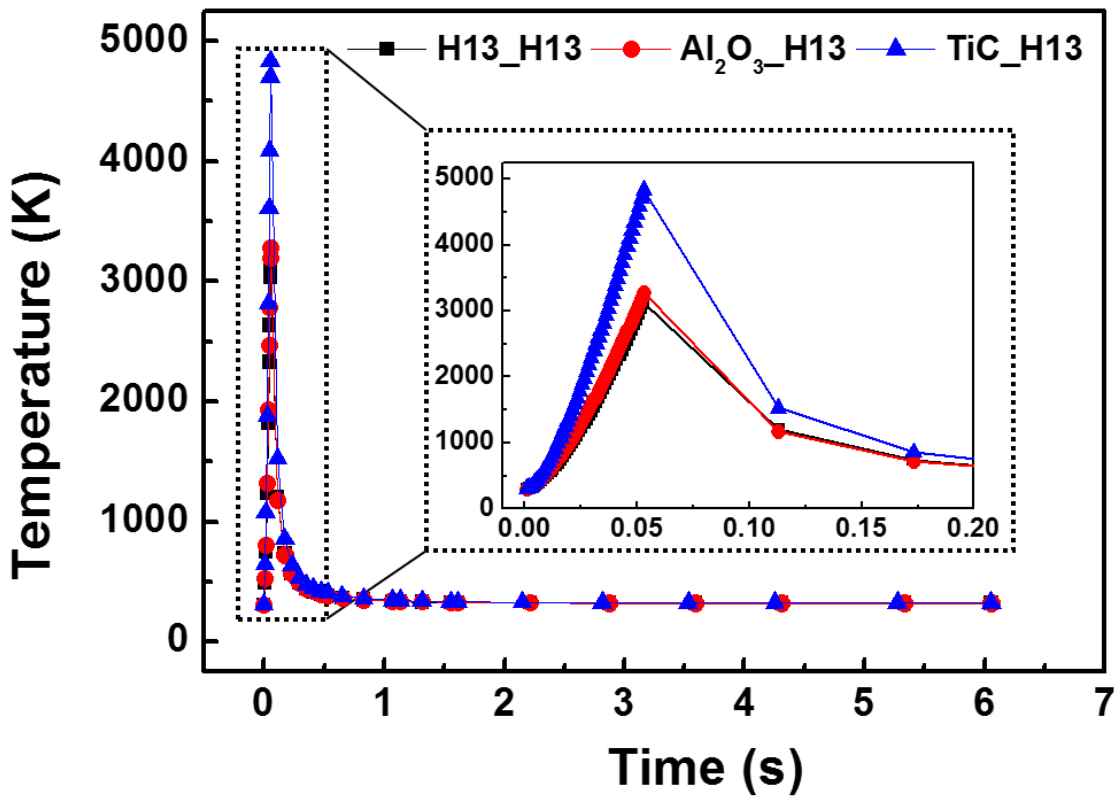


Fig. 5.4 Temperature vs time distribution of H13/H13, Al₂O₃/H13 and TiC/H13 cladding samples.

5.2.2 Residual stresses analysis

In coaxial Laser Cladding process, laser heat source and molten material are supplied along the same axis to the substrate surface. The heated material expands during heating while cooled material restricts the expansion of heated material. During cooling, clad and heated substrate materials contract and get restricted to contract by the surrounding materials. These phenomena cause tensile stresses in the clad, interface and the substrate near the clad. If the tensile stress is above the yield stress of material, plastic flow occurs in the material which is detrimental for any component under application of loads.

Residual stress distribution in X and Y directions at CD line has been predicted and is shown in Fig. 5.5 (a). Residual stress distribution of H13/H13, Al₂O₃/H13 and TiC/H13 cladding samples are given in Fig. 5.5 (b), (c) and (d) respectively. In all samples, tensile residual stress formed in the clad in X direction and decreased inside the substrate. In case of H13/H13 sample, maximum equivalent stress (SEQV) at path CD was 794 MPa, found at the top of clad, shown in Fig. 5.5 (b), which is below the yield stress of H13 steel (1650 MPa [176]). In Al₂O₃/H13 sample, equivalent stress (SEQV) at the top of the clad was 1220 MPa which was lower than equivalent stress (1359 MPa) in TiC/H13 sample. The formation of lower stress in Al₂O₃/H13 sample than TiC/H13 sample can be explained using the concept of mismatch of thermal strain of clad and substrate. In the author's previous work, it was shown that the mismatch of thermal strain between Al₂O₃ and H13 steel are lower than the mismatch of thermal strain between TiC and H13 steel [177]. However, in both Al₂O₃/H13 and TiC/H13 samples, equivalent stresses (SEQV) were higher than the tensile strength of Al₂O₃ (665 MPa [174]) and TiC (258 MPa [167]) which could form cracks in the clad. For all samples, compressive residual stresses were found in Y direction as structural constraint was applied in this direction. The distribution of shear stress at CD line of H13/H13, Al₂O₃/H13 and TiC/H13 cladding samples are given in Fig. 5.6. The value of shear stresses in all samples are two order lower than the generated tensile stresses. So, it can be said that the formed shear stress may not have same detrimental effect as tensile residual stresses for the cladded samples.

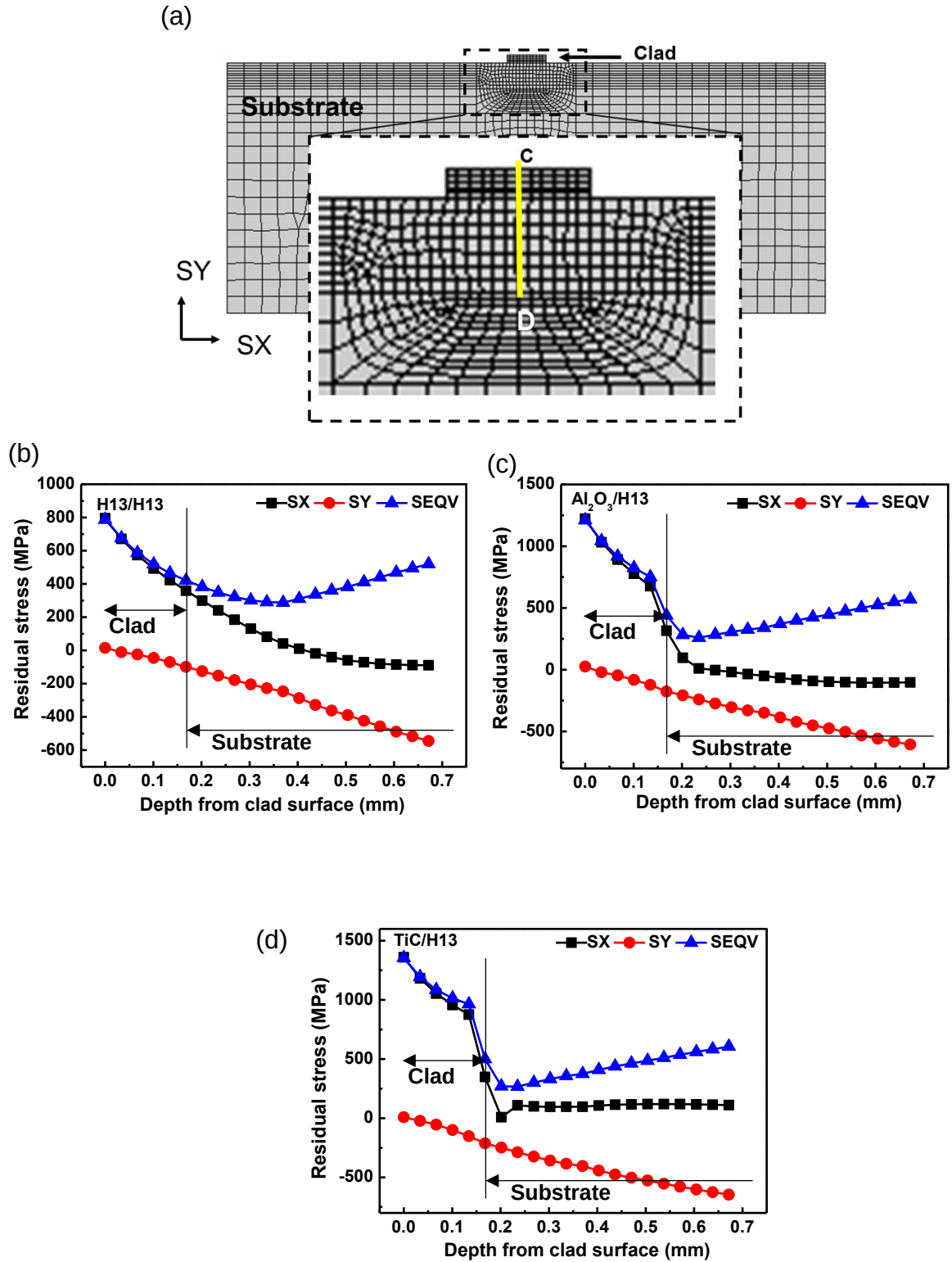


Fig. 5.5 (a) Geometry and mesh, residual stresses distribution at CD line in X and Y direction are given for (b) H13/H13, (c) $\text{Al}_2\text{O}_3/\text{H13}$ and (d) TiC/H13 cladding systems.

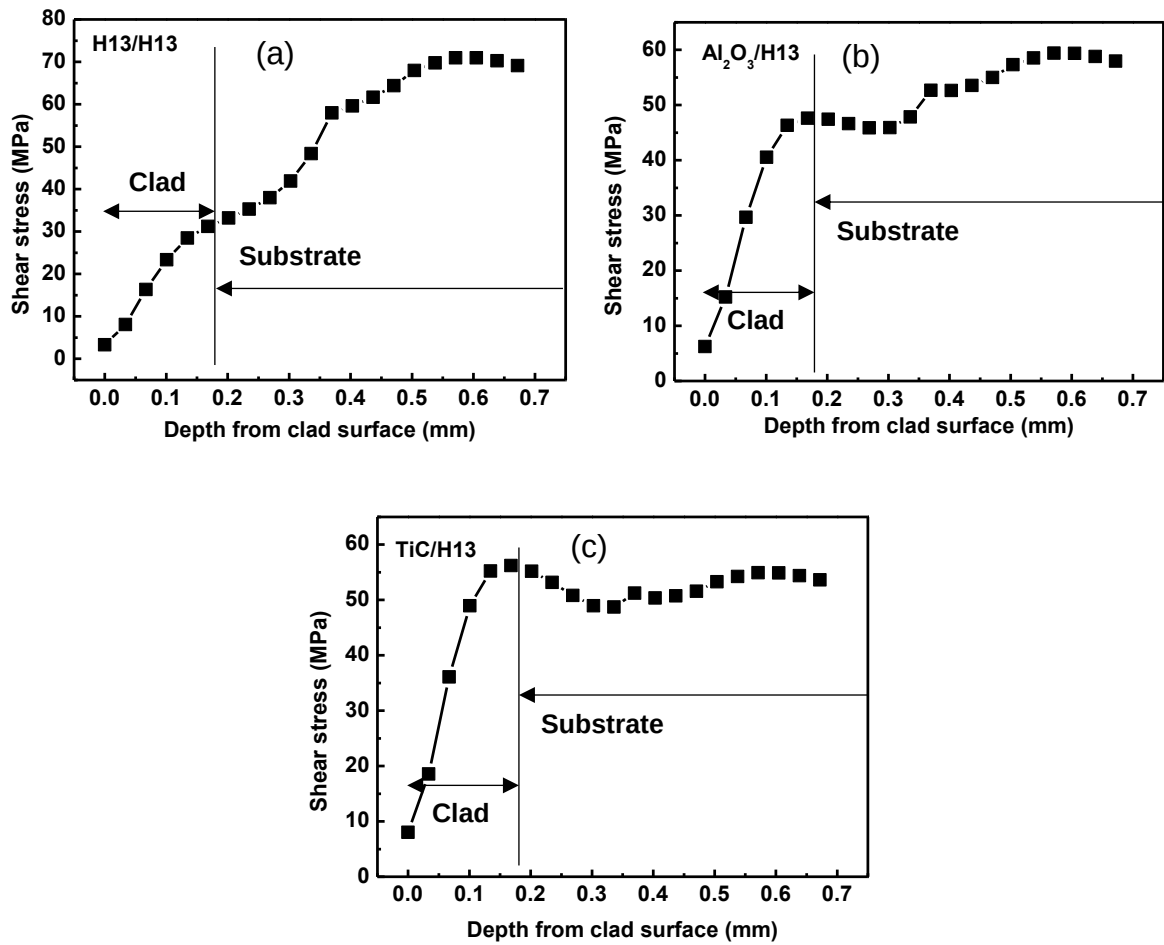


Fig. 5.6 Residual stresses (shear stresses) distribution at CD line in X and Y direction are given for (b) H13/H13, (c) Al₂O₃/H13 and (d) TiC/H13 cladding systems.

5.3 Conclusion

2D thermo-mechanical model has been developed to predict temperature distribution and residual stresses distribution of Laser Cladding process for deposition of H13 steel, Al₂O₃ and TiC cladding materials on the H13 substrate material. From temperature distribution, it was found that all cladding materials went above the melting temperature at the interface. TiC coating formed higher temperature gradient because of its highest peak temperature. The predicted maximum equivalent residual stress of H13/H13, Al₂O₃/H13 and TiC/H13 samples were 794 MPa, 1220 MPa and 1359 MPa in the middle of the clad respectively. The generated residual stress of Al₂O₃/H13 sample was lower than the TiC/H13 samples

due as the total strain was lower between Al_2O_3 and H13. It can be claimed that the deposition of H13 clad material could be appropriate for repair application as the generated stress is far below than the yield stress of H13 steel (1650 MPa). However, deposition of Al_2O_3 and TiC deposition could form cracks in the clad.

6 3D moving heat source model of Ti6Al4V (substrate)/Ti6Al4V (clad) sample

As the temperature load changes along the direction/movement of laser heat source, the development of 3D model is required to fully understand the process. In this chapter, a 3D thermo-mechanical model of Ti6Al4V/Ti6Al4V (clad/substrate) material has been developed using a moving heat source. This model was used to predict the temperature distribution and residual stress distribution. From the predicted temperature distribution, the heating and cooling rate and microstructures in the clad and substrate were predicted. The predicted stress distribution was tensile in nature in the clad and in substrate near the interface. Additionally, model verification was performed to see the accuracy of the mesh and the applied boundary conditions.

6.1 Model set up

6.1.1 3D Geometry and mesh

For this model, the geometry of the substrate and the clad layer was adopted from experimental results by Y. Sun et al. [15]. The dimensions of the substrate geometry were 110 mm width, 110 mm height and 13 mm long. The clad height and width were 0.5 mm and 1.2 mm respectively [15]. However, the dimensions of the substrate geometry was far larger than the clad size and, due to high cost of calculation, the dimension of substrate was changed to as 5 mm width, 3 mm height and 16 mm long [71]. The model consisting of the substrate and the clad is given in Fig. 6.1. In 3D meshing, half of the geometry was taken by considering the symmetry along the laser scanning direction. For meshing, transitional mapped mesh technique was applied to achieve accurate calculation of the temperature

distribution and residual stresses distribution as shown in Fig. 6.2. The clad layer and part of the substrate area were meshed with finer elements as the heat / temperature distribution is mostly restricted in that area.

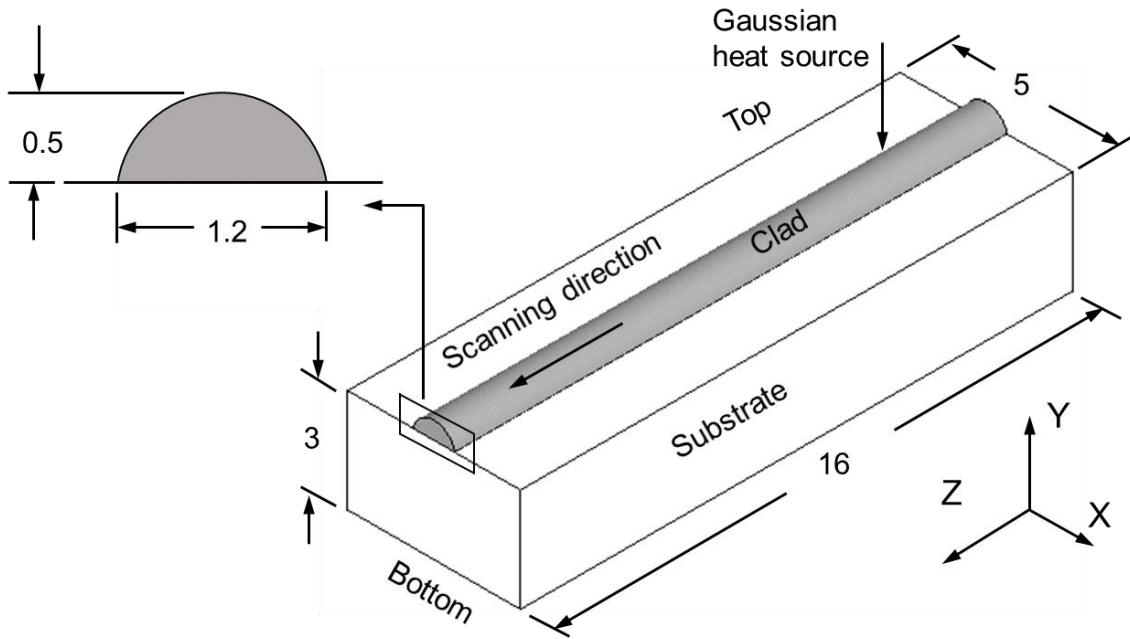


Fig. 6.1 The geometry of 3D model. All dimensions are in mm.

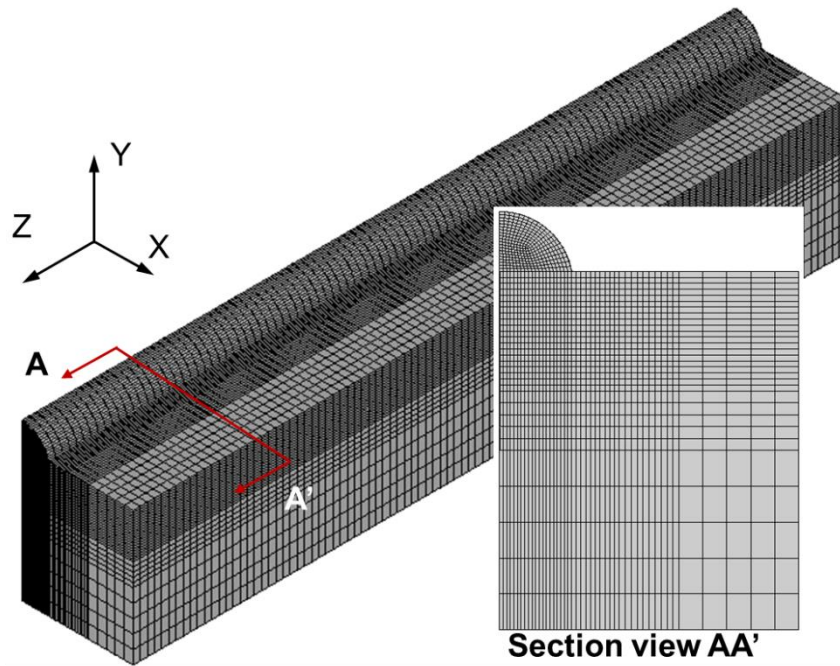


Fig. 6.2 The meshing of the 3D symmetry model.

Rest of the substrate area was gradually meshed with coarser elements by following ratio between fine and coarse element size. This non-uniform mesh distribution helps to minimise the number of elements. The total number of elements and nodes are 121497 and 100900 respectively.

The solid 70 hexahedron element having 8 nodes with a single degree of freedom, temperature, at each node was used in the mapped mesh area for transient thermal analysis. After transient thermal analysis, this model was coupled with mechanical analysis. In mechanical analysis, the solid 70 element switched to solid 185 element having three degrees of freedom at each node (translations in the nodal X, Y, and Z directions). In order to deposit powder on substrate, the element birth and kill technique was used. Before applying heat source, the elements of clad was killed and deactivated. When the heat source was applied to the laser-scanned region, the deactivated elements were activated with the moving heat source. Before analysis of the model, the mesh convergence was done to predict the accurate results given in Fig. 6.3.

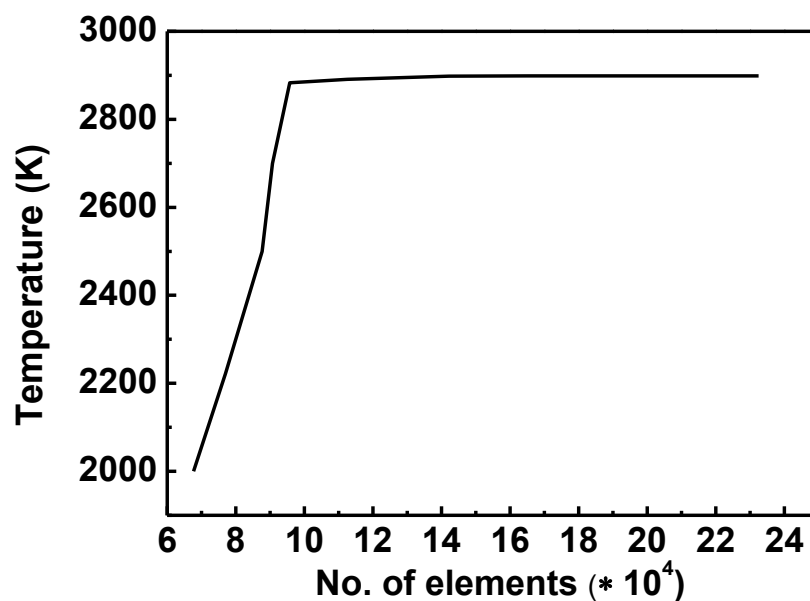


Fig. 6.3 Mesh convergence of 3D of model.

In order to do mesh convergence, initially, all lines were divided into 10 divisions. After that, number of divisions in all lines in the geometry were increased. The elements in lower part of the substrate were kept relatively coarse. As the heat was concentrated in the clad and near surface of the substrate, elements in these area were refined several times until a consistent temperature had been achieved. It was found that above 10^4 elements, a consistent temperature was achieved. The smallest element size in the clad was $160 \mu\text{m} \times 15.3 \mu\text{m} \times 12.7 \mu\text{m}$.

6.1.2 Material properties

In this model, Ti6Al4V material was used as substrate and clad material. The chemical composition of Ti6Al4V material is given in Table 6.1.

Table 6.1 The chemical composition of Ti6Al4V material [71].

Composition	Ti	O	Al	V	Fe	C	N	H	Other
Wt%	~89.438	0.09	6	4	0.04	0.02	0.01	0.002	≤ 0.4

The solidus and liquidus temperature of Ti6Al4V material are respectively around 1843 K and 1941 K. Therefore, there is a mushy zone of Ti6Al4V alloy. In order to calculate the temperature in this zone, latent heat of fusion was added to specific heat as an additional energy E^* given in Eq. 6.1.

$$E^* = \frac{C_S(T) + C_L(T)}{2} + \frac{L}{T_L - T_S} T_S \leq T \leq T_L \dots\dots\dots(6.1)$$

where, C_S and C_L are specific heat capacity of solid and liquid Ti6Al4V alloy respectively, T_S and T_L are the solidus and the liquidus temperature respectively. L is the latent heat of fusion which is 292 kJ/kg [71]. After reaching the melting point, the specific heat remains constant 1126 J/kg.K. The boiling temperature is about 3808 K. The constant density and poisson ratio were used as 4440 kg/m³ and 0.32

respectively [71]. The temperature dependent thermal and mechanical properties are given in Fig. 6.4 and Fig. 6.5 [71,178]. The governing equation and boundary conditions are given in appendix C.

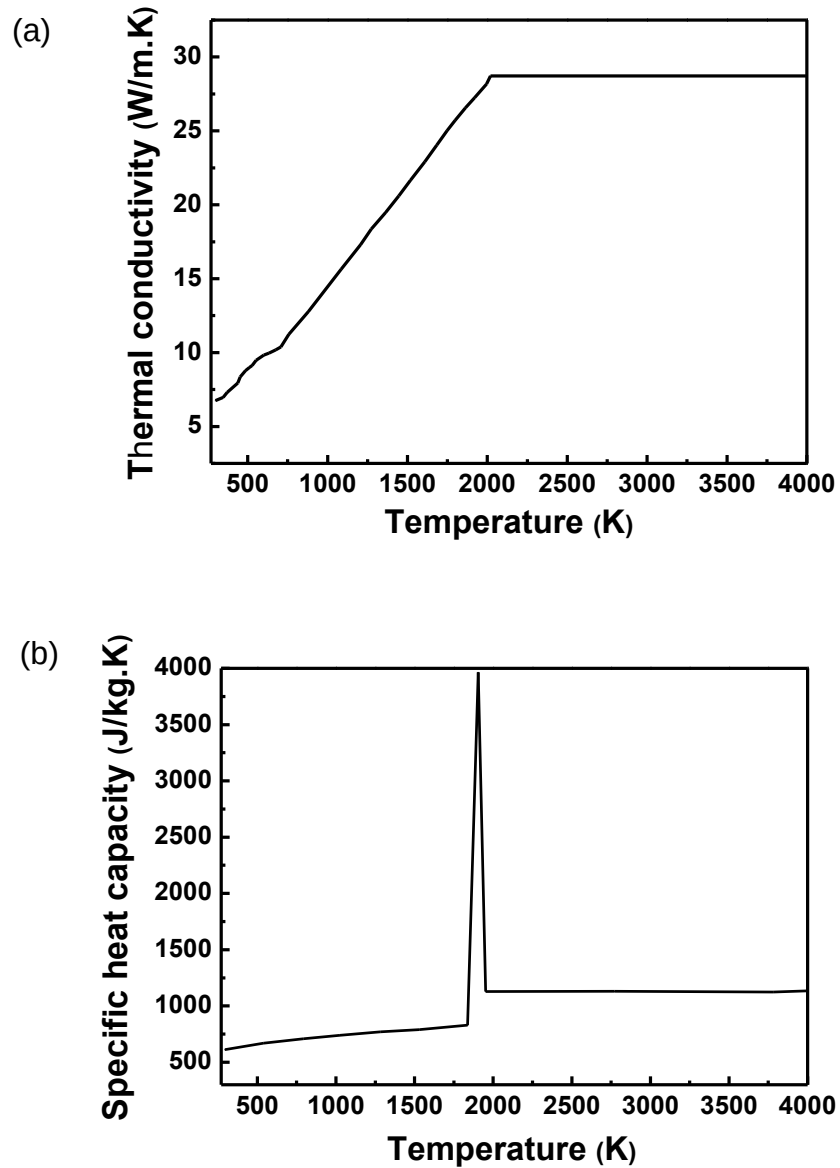


Fig. 6.4 Temperature dependent thermal properties (a) thermal conductivity and (b) specific heat capacity.

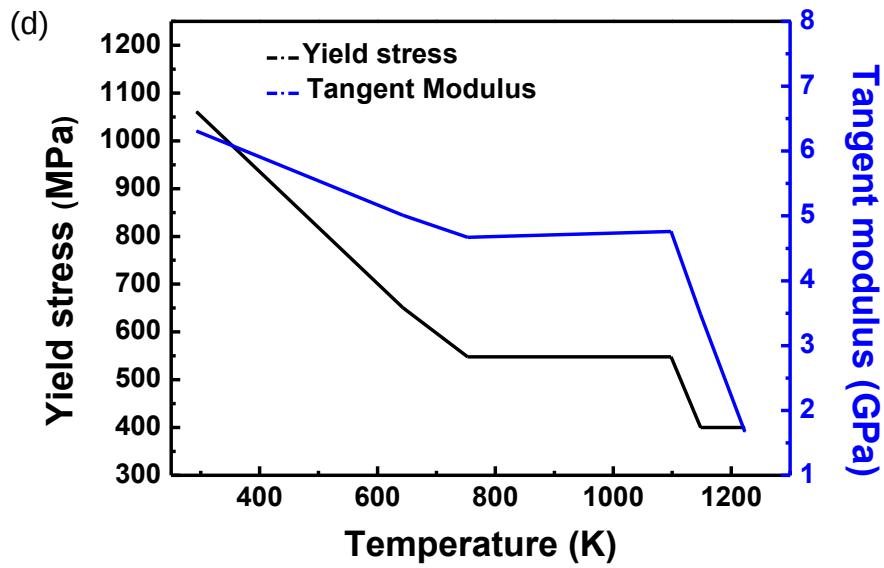
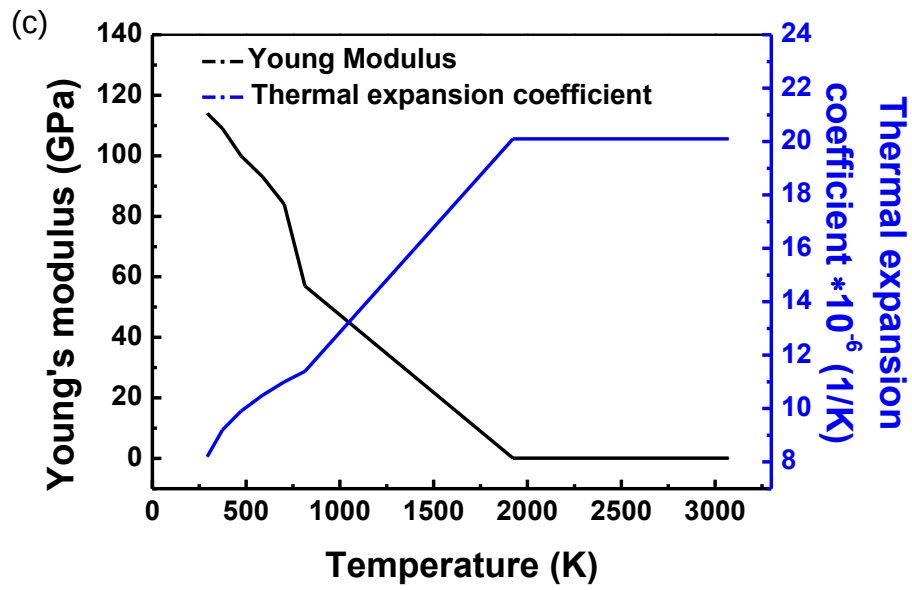


Fig. 6.5 Temperature dependent mechanical properties (a) Young's modulus and thermal expansion coefficient and (b) Yield stress and tangent modulus of Ti6Al4V.

6.2 Verification of the model

The aim of this section is to reproduce the simulated results from a well-established model. The simulated work by Hao et al. was taken to perform the benchmark [71]. In their work, a FEM model was presented which is able to conduct the thermal stimulation of laser cladding process, and confirmed by the experimental investigation. A spherical Gaussian heat source was adopted rather than the Gaussian planar heat source in the thermal model. Because, the application of the spherical Gaussian heat source provide better accuracy with melt pool dimension than the Gaussian planar heat source. The radius of heat source was adjusted iteratively according to the difference between the melt pool depth from experimental sample and predicted melt pool boundary. Additionally, it was mentioned that the dimension of heat source does not remain constant during experiments. Therefore, there is no physical relation between the actual heat source radius and implemented radius in their model. Latent heat of fusion was accounted due to phase transformation during the melting and solidifying process. Furthermore, the heat and mass transfer in laser cladding process was introduced by the birth and death of elements technology.

In the current work, the model has been developed using same process parameters and given dimensions of the clad and substrate in the literature. The laser beam radius was fixed iteratively based on the melt pool depth. Additionally, the spherical volumetric heat source could not produce exactly the same shape of melt pool. Therefore, the distribution of the heat source has been optimised to obtain required shape of the melt pool. The temperature distribution was predicted using laser parameters: 600 W laser power and 700 mm/min scanning speed.

The predicted temperature distributions of developed model by Hao et al. and developed separately by author of this thesis are given in Fig. 6.6.

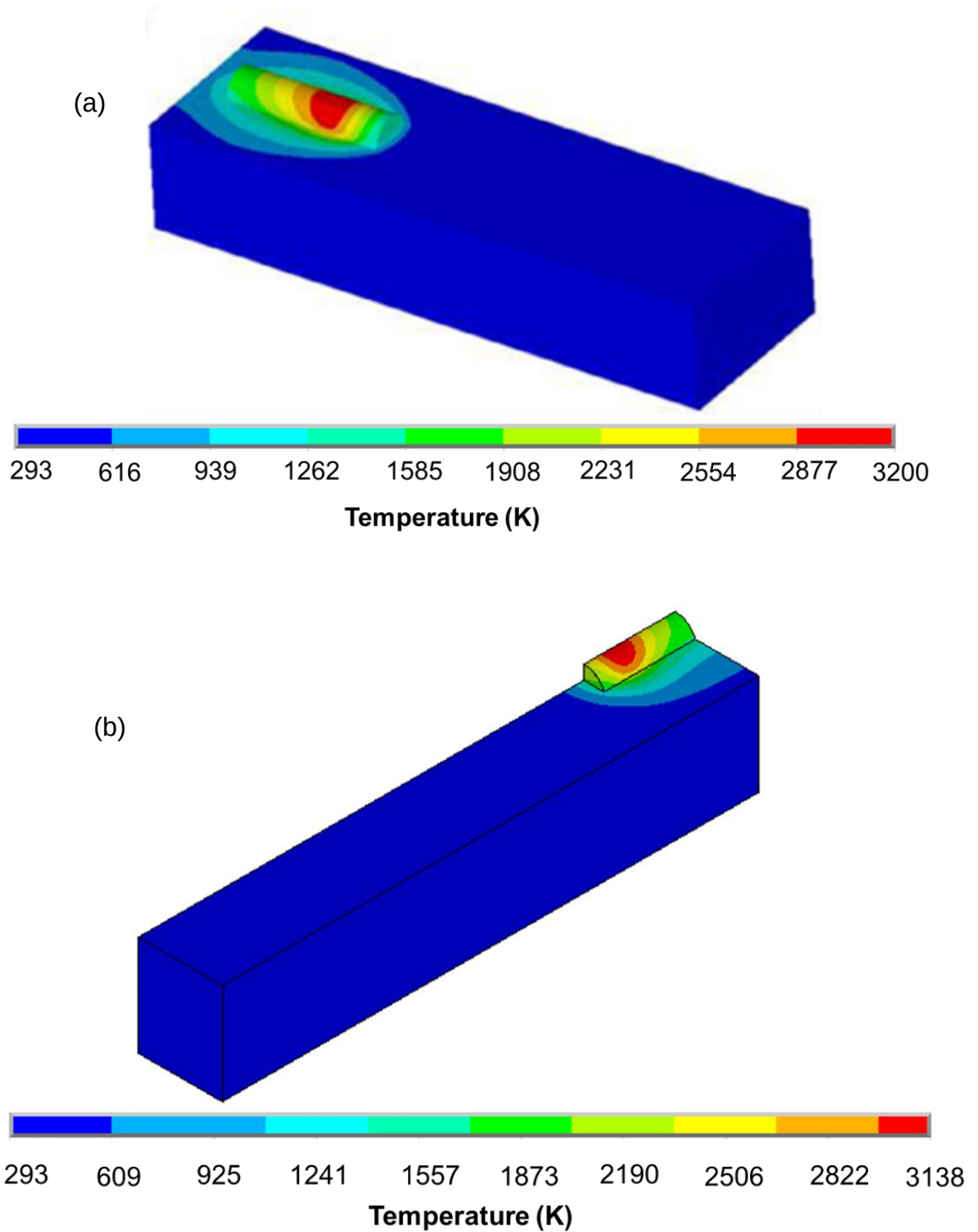


Fig. 6.6 The predicted temperature distribution (a) developed model by Hao et al. [71] and (b) developed model by author.

The predicted temperature by the author of this thesis is 62 K lower than the developed model by Hao et al. which results 1.9% deviation. The difference of temperature could be the reason of differences in materials properties, number of sub steps, iteration number, the iterative value of laser heat source diameter, the distribution of heat source and the position of heat source. Additionally, Hao et al. validated the predicted results with experimental results, shown in Fig. 6.7. The simulated melt pool depth ($D_p=0.41$ mm) and the actual melt pool depth (from experiments) ($D_a= 0.41$ mm) are same. In this work, the depth of melt pool, D_{TW} was found to be 0.406 mm which is very near (0.41 mm) to the results reported by Hao et al.

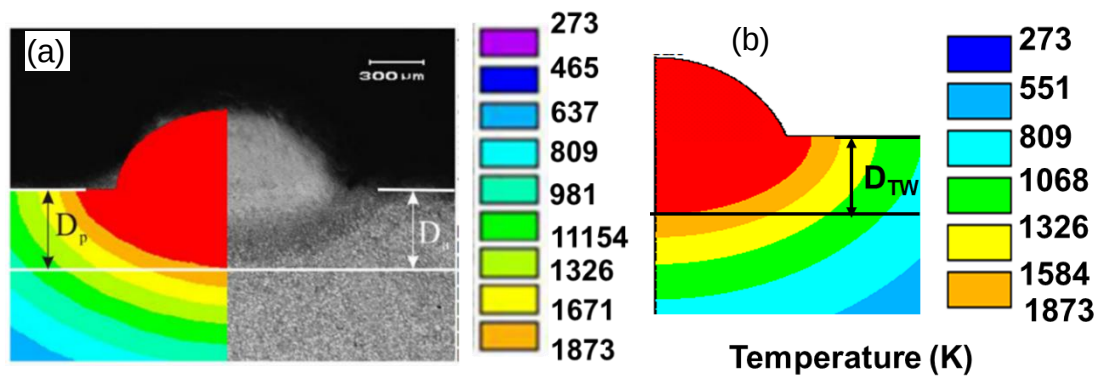


Fig. 6.7 The melt pool depth of (a) modelling and experimental results by Hao et al. and (b) current work by author.

The predicted results of this current work and the developed model of Hao et al. are summarised in Table 6.2.

Table 6.2 Comparison of predicted results between the model of Hao et al. [71] and the current model.

Condition	Predicted results by Hao et al.	Predicted results by author	% of difference
Peak temperature	3200 K	3168 K	1.9
Melt pool depth at the centre of clad	0.41 mm	0.406 mm	0.97

From this analysis, it can be said that the technique of mesh and boundary conditions used to develop the model in this thesis accurately predict temperature distribution and melt pool dimension of another model in the literature.

6.3 Results and discussion

6.3.1 Optimization of process parameters for 3D model

In order to develop the 3D thermo-mechanical model, Ti6Al4V powder was deposited on the substrate of Ti6Al4V material. Laser parameters and heat source are the important process parameters to develop a model. Laser parameters were taken from the experimental results. In simulation, the heat source has a significant influence on the computation accuracy and efficiency of the thermal model. Additionally, Hao et al. mentioned that there was no physical relation between the implemented heat source radius and the real physical heat source radius as the dimension of the heat source does not remain constant in experiments [71]. Therefore, heat source radius was used as a tuning parameter. In this work, volumetric spherical Gaussian heat source has been used to predict the temperature distribution. The optimised process parameters (laser power and laser beam radius) are given in Table 6.3.

As 600 W laser power, 0.7 mm beam diameter and 700 mm/s scanning speed can melt the clad and the substrate at the end of the clad, this set of process parameters were used for further analysis of the model.

Table 6.3 Optimisation of process parameters (laser power and beam radius).

Radius (mm)	Power (W)	Scanning speed (mm/min)	Peak temperature (K)	Melt pool depth (mm)	Comment
0.7	552	700	3109	0.47	Clad get melted.
0.7	600		3201	0.5	Clad and substrate material at the end of the clad melted perfectly.
0.7	650		3396	0.56	Clad material was melted perfectly.
0.8	552		2778	0.396	Two end of the clad material along the width did not reach melting point.
0.8	600		2989	0.45	Two end of the clad along the width did not reach melting point.
0.8	650		3201	0.566	Clad material was melted perfectly.
1	552		2200	-	Entire clad did not reach melting temperature.
1	600		2350	-	Entire clad did not reach melting temperature.
1	650		2524	-	Entire clad did not reach melting temperature.

6.3.2 Temperature distribution

Fig. 6.8 shows the isothermal distribution in a single track of the Laser Cladding process with laser power of 600 W, scanning speed of 700 mm/s and laser beam diameter of 0.7 mm after 1.339 s.

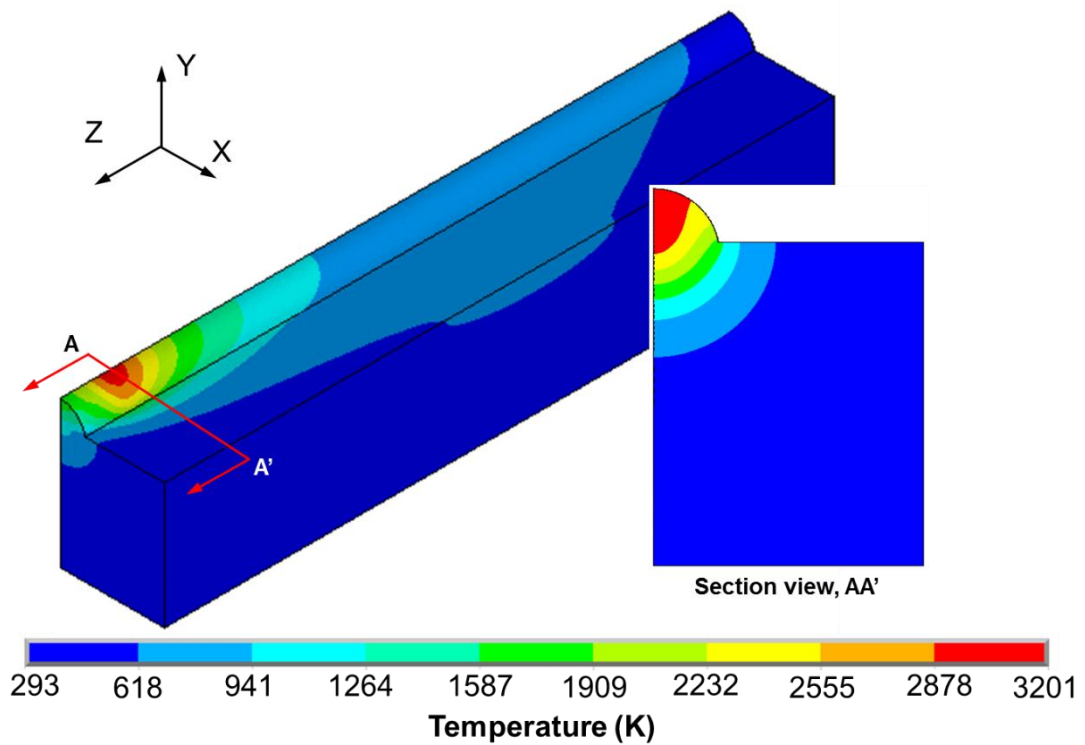


Fig. 6.8 The temperature distribution of the 3D model at 1.339 s. Power = 600 W, beam diameter = 0.7 mm and scanning speed = 700 mm/s.

From the temperature profile, we can observe the shape and distribution of the heat affected area such as the clad zone, melt pool and heat affected zone (HAZ) shown in Fig. 6.9.

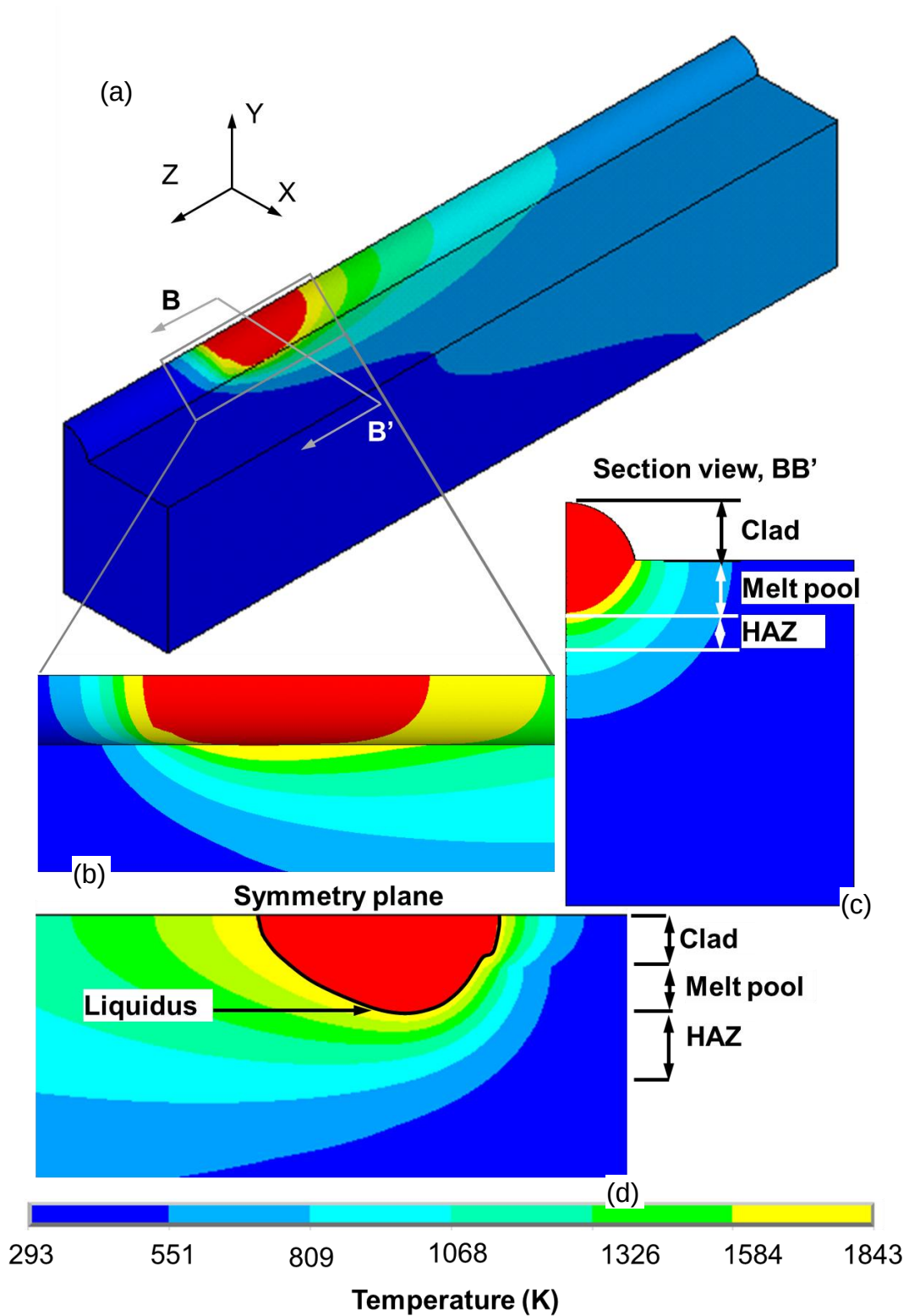


Fig. 6.9 (a) The temperature distribution of the 3D model at 1.339 s. Power = 600 W, beam diameter = 0.7 mm and scanning speed = 700 mm/s, (b) selected top view of melt pool, (c) section view BB' and (d) view at symmetry plane.

In order to observe the shape of the heat inputted area, selected top view, section view and view at symmetry plane have been shown in Fig. 6.9 (b), (c) and (d) respectively. The selected top view of melt pool is given to show the distribution of heat in the clad. The section view shows the height of clad, melt pool and heat affected zone (HAZ). The view of symmetry plane shows the shape of the melt pool. Higher melt pool depth was found on the direction of laser speed due to the higher concentration of heat input.

The dimensions of the predicted height of the clad, melt pool and HAZ are shown in Fig. 6.10. The height of the clad is the deposited Ti6Al4V material which was 0.5 mm. The melt pool height (~0.48 mm) was defined where the material temperature was higher than the solidus temperature [15]. Finally, the heat affected zone (0.23 mm), where temperature was higher than the β transus temperature of (1287 K) [179].

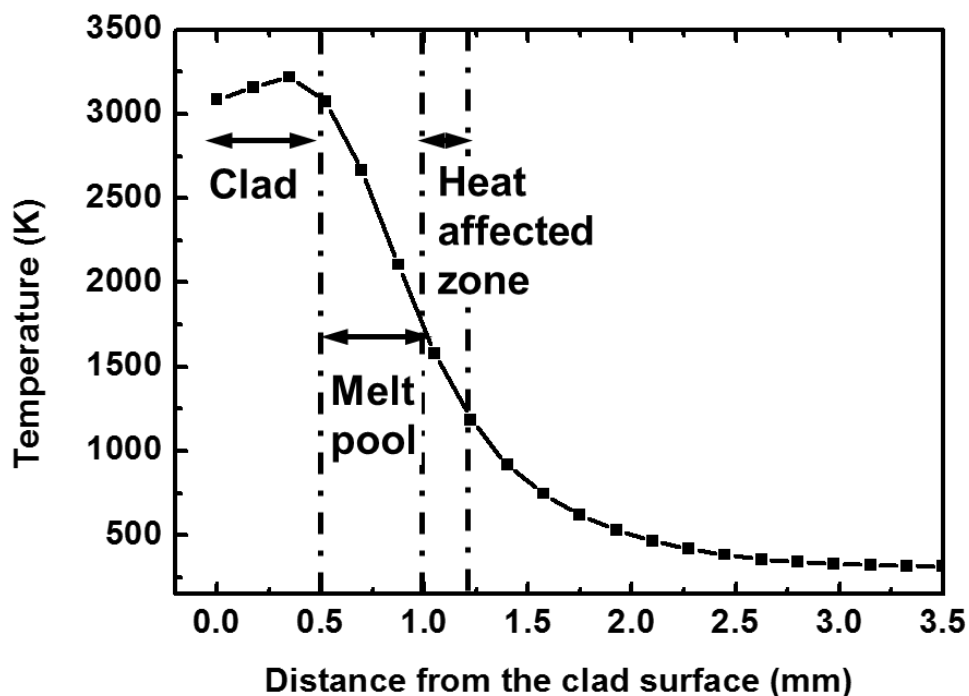


Fig. 6.10 The temperature distribution from the clad surface to the bottom of the substrate.

Fig. 6.11 shows the temperature evolution, heating cycles and cooling cycles at three different locations at the interface of the clad and the substrate during the laser cladding process. Fig. 6.11 (a) shows the positions of points 1, 2 and 3 in the geometry. The temperature evolutions at these points with time are given in Fig. 6.11 (b). The predicted temperature profile offers the formation time of the melt pool, heating rate and cooling rate. At points 1 (after 0.412 s), 2 (after 0.7725 s) and 3 (after 1.133 s), the peak temperatures were 3078 K, 3114 K and 3031 K respectively. This temperature was higher than the solidus temperature of Ti6Al4V (1843 K) which ensured the perfect melting of the clad and the substrate surface. This highest temperature in the clad was 3201 K due to the maximum laser intensity at this location.

The maximum heating and cooling rate were found 2.45×10^4 K/s and 1.1×10^4 K/s in the clad, shown in Fig. 6.11 (c). From cooling rate, we can predict the phases in the microstructure. It is reported by J. Yang et al. that during the deposition of Ti6Al4V in selective laser melting process, maximum cooling rate reached 10^8 K/s which produced α' martensite [180]. Another report shows that 410 K/s cooling rate also produced acicular α' martensite [181]. In this work, the cooling rate is 1.1×10^4 K/s in the clad and melt pool and the temperature was above the liquidus temperature (1941 K). So, it can be claimed that α' martensite could form in the clad and melt pool.

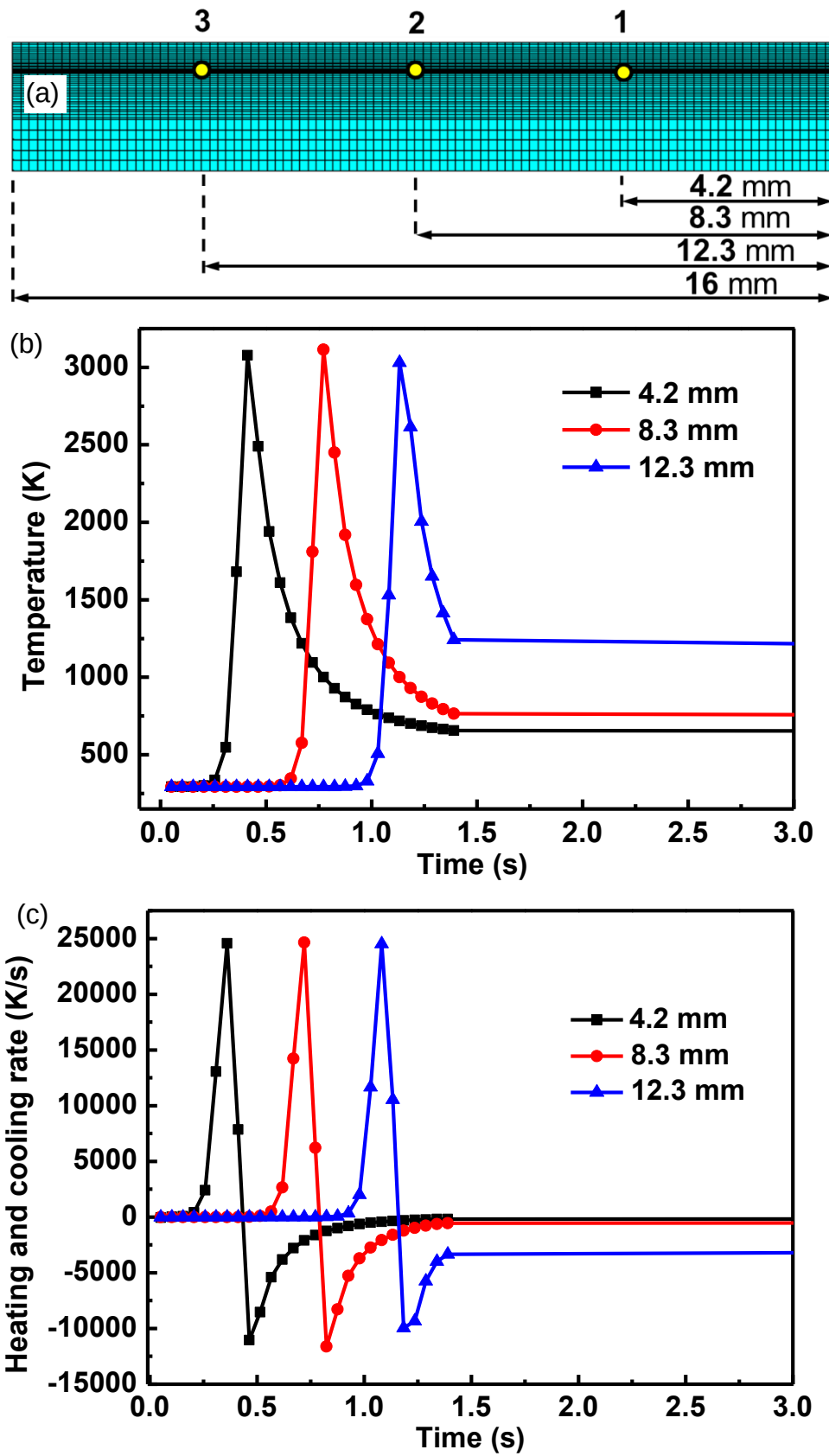
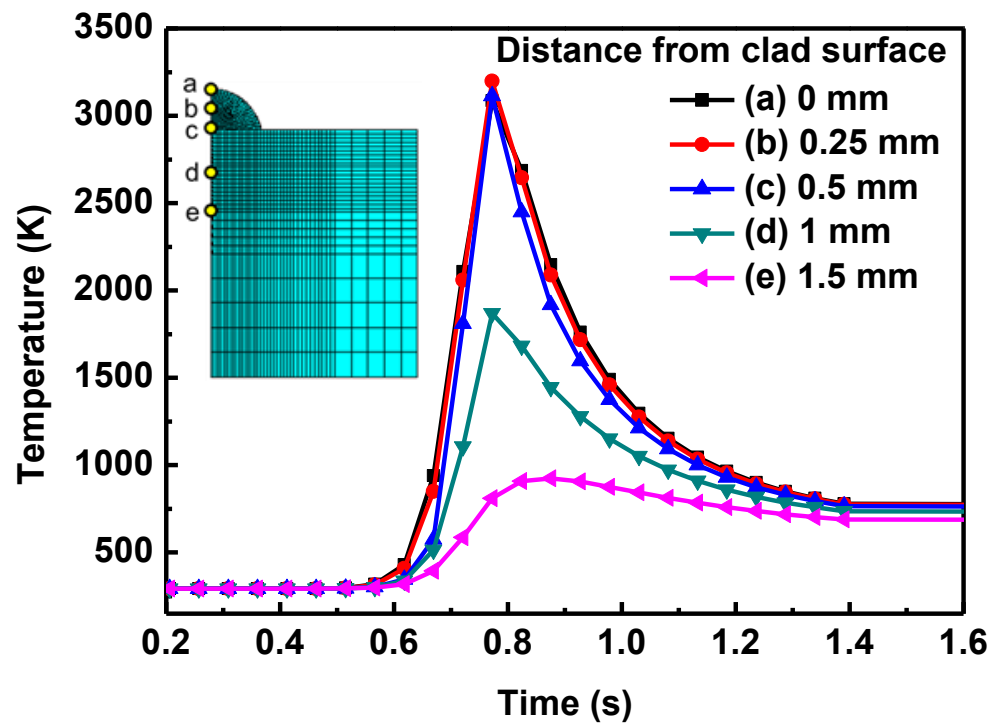


Fig. 6.11 (a) Monitoring position of temperature distribution, (b) temperature distribution and (c) heating and cooling rate at three different positions.

The temperature distribution, heating cycles and cooling cycles for five locations along the depth in the middle of the geometry are given in Fig. 6.12. Points *a*, *b*, *c*, *d* and *e* are in position from the surface of the clad 0 mm, 0.25 mm, 0.5 mm, 1 mm and 1.5 mm respectively. The temperature distribution in Fig. 6.12 (a) shows that the material in *a*, *b*, *c* and *d* locations reached the temperature above the solidus temperature (1843 K). Below the location *d*, the temperature was lower than the solidus temperature (1843 K). Therefore, the boundary of melt pool was defined up to the location *d*. At locations *a*, *b*, *c*, *d* and *e* the peak temperature were 3126 K, 3147 K, 3114 K, 1869 K and 811 K respectively. The temperature at locations *a*, *b* and *c* are almost similar. Additionally, temperature was dropping to *d* and *e* locations which was predicted in conceptual model, see section 3.2. The heating cycles and cooling cycles at points *a*, *b*, *c*, *d* and *e* are given in Fig. 6.12 (b). The heating rate (2.45×10^4 K/s) at location *c* (at interface) was maximum as the heat source was applied at the interface of the clad and the substrate. The cooling rate at *a*, *b* and *c* locations were similar while at location *d*, the cooling rate was lower than these point. The cooling rate at location *c* was 1.1×10^4 K/s. During solidification, liquid materials from point *a* to *c* pass the solidus temperature (1843 K), β transus temperature (1288 K) and martensitic transformation temperature (~ 1073 K) and finally, produce the acicular α' martensite [180,182]. The material in HAZ reaches above the β transus temperature (1267 K) and results mixture of the acicular α' martensite and fine Widmanstatten structure as the cooling rate is relative slow [179]. Finally, the location which is below martensitic transformation temperature (~ 1073 K) will have the same micro-structure of primary substrate phase before heat treatment.

(a)



(b)

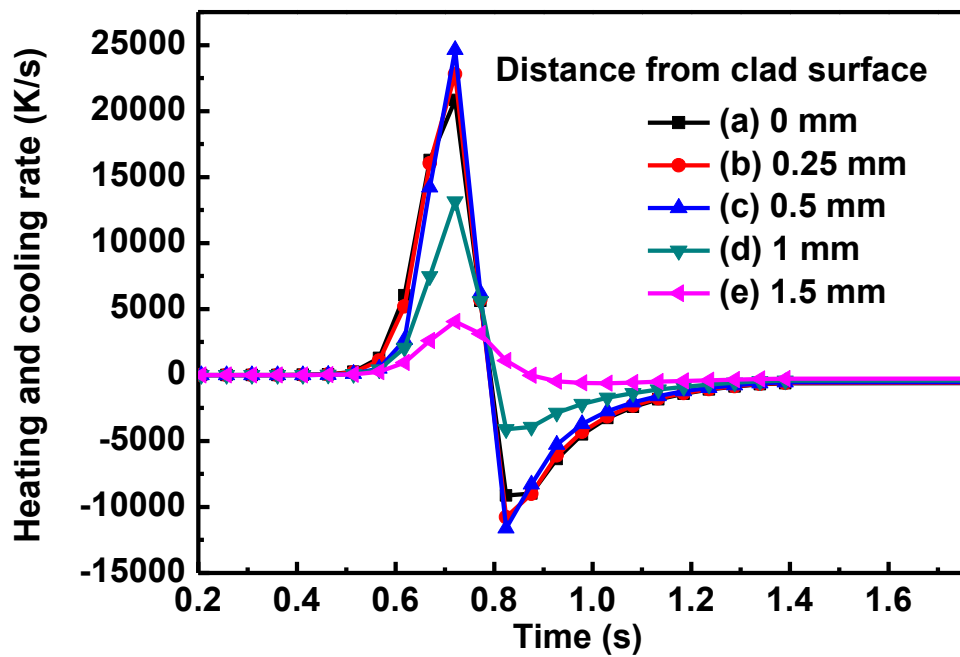


Fig. 6.12 (a) Temperature distribution at five positions along the depth and (b) heating and cooling rate at these positions.

6.3.3 Residual stress distribution

One of the important applications of Ti6Al4V material is high temperature applications such as blades for aircraft turbines and steam turbine which goes through thermal stresses, local loading and cyclic loading. So, the stress state in these component is very crucial especially when the surface of these component is treated by laser heat source. Fig. 6.13 shows the residual stress distribution in X (SX), Y (SY) and Z (SZ) directions at the path MN for understanding the nature of stresses in the clad and near surface of the substrate. The tensile residual stresses were found in X and Z directions for all samples. Tensile stress in X direction was increased from the clad surface to substrate and turned to compressive after 1.05 mm in the substrate. In Z direction, tensile residual stress was increased from clad surface to substrate. In both X and Z directions, maximum stress was generated at the interface of the clad and substrate, then decreased inside the substrate. However, stress in Y direction was mostly compressive as displacement constrain was applied in this direction.

Fig. 6.14 shows the residual stress distribution in X (SX), Y (SY) and Z (SZ) directions at the path OP. It shows that tensile residual stress formed in X and Z directions. Tensile stresses in both directions were increased from the symmetry plane to the end of the clad and turned to compressive stress inside the substrate. Maximum tensile stresses were found at the end of the clad material in all directions.

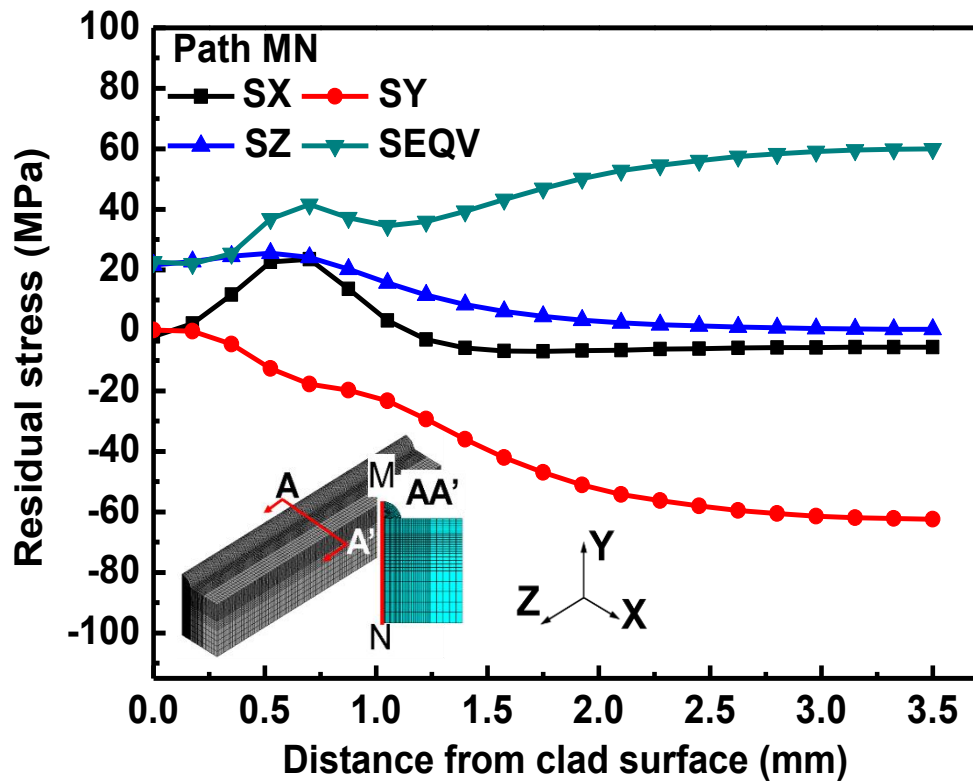


Fig. 6.13 The residual stresses distribution at the path MN, from the top of the clad surface to the bottom of the substrate.

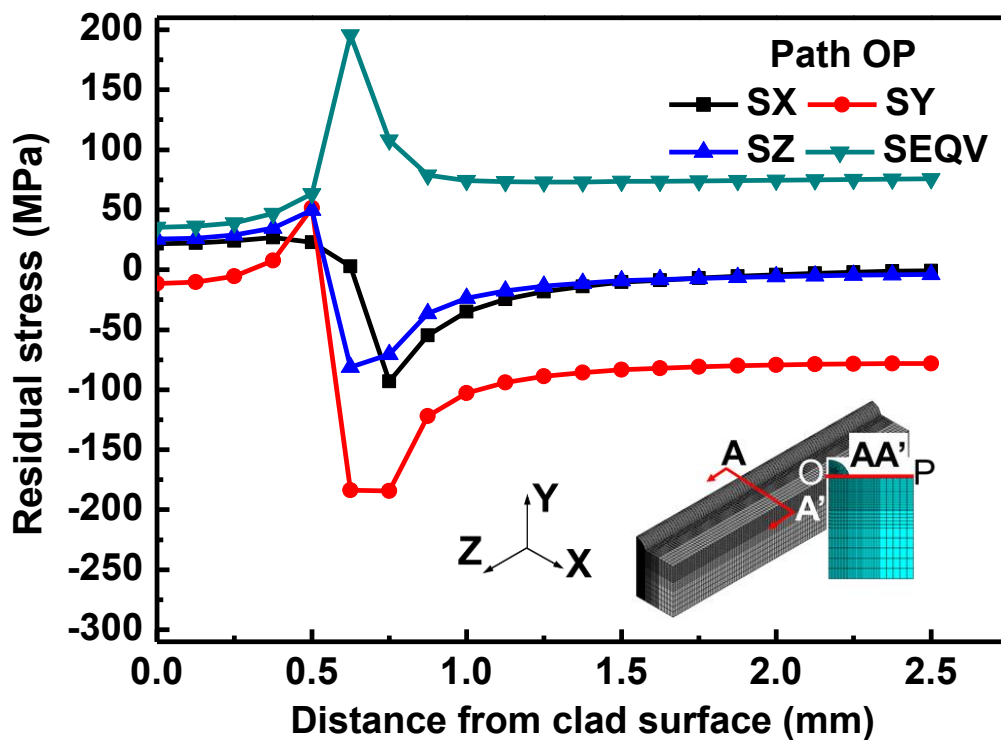


Fig. 6.14 The residual stress distribution at the path OP, from the symmetry plane to the right end of the substrate.

The equivalent stresses (SEQV) in path MN and OP were predicted. The maximum tensile residual stress (108 MPa) and equivalent von Mises stress (200 MPa) formed at the end of the clad which is much below than the yield strength (1061 MPa [178]) of Ti6Al4V material. Furthermore, the generated shear stresses were observed in the clad and substrate. The generated shear stress on XY, YZ and ZX planes were two order less than the generated tensile residual stresses in all direction. Therefore, there will be no crack formation or growth of cracks in this sample due to shear stresses. Also, it was found by Cottam et al. that after repairing aircraft component of Ti6Al4V, around 150 MPa residual stress was formed at the clad and substrate interface [183]. The generated residual stress was lower than the yield strength (1100 MPa) of Ti6Al4V. So, this process will be applicable of repair application. In addition, the pattern of formation of residual stresses in X and Z direction are similar with the predicted residual stresses for repairing application reported by Chew et al.[10].

6.4 Conclusion

A thermo-mechanical model based on finite element method has been developed to determine the temperature distribution and residual stresses. In order to develop this model, benchmarking has been done to verify the accuracy of the mesh and boundary conditions. Temperature history offers the knowledge about the peak temperature at the interface (3201 K), shape and distribution of heat in clad and the substrate, depth of melt pool (0.5 mm) and HAZ (0.23 mm), the formation time of melt pool, maximum heating rate (2.45×10^4 K/s) and cooling rate (1.1×10^4 K/s). Finally, micro-structure was predicted. Material in the clad and melt pool generated the acicular α' martensite as the material experienced high cooling rate (1.1×10^4 K/s) and the temperature was above the liquidus temperature (1941 K). The material

in HAZ reached above the β transus temperature (1267 K) and experienced medium to slow cooling rate which resulted combination of acicular α' martensite fine Widmanstätten structure. Finally, material which was below martensitic transformation temperature (~ 1073 K) will have the same micro-structure of primary substrate phase before heat treatment. Tensile residual stresses were found in the clad and near substrate. Maximum tensile stress was 108 MPa which is far below the yield strength (1061 MPa) of Ti6Al4V material.

7 3D model of Al₂O₃/Ti6Al4V and TiC/Ti6Al4V samples

In this chapter, 3D thermo-mechanical models have been developed numerically using ANSYS'18 multi-physics platform to compare generated residual stresses among different cladding materials. Three cladding materials (Al₂O₃-1, Al₂O₃-2 and TiC) were deposited on the surface of the Ti6Al4V substrate. Laser power for each sample was optimised. The optimised laser power of Al₂O₃/Ti6Al4V and TiC/Ti6Al4V are 250 W and 380 W respectively. The predicted temperature distribution ensure the proper melting of the clad and the substrate material. From the cooling rate, microstructures in the clad and substrate were predicted. Tensile stresses were found in the clad of TiC/Ti6Al4V and Al₂O₃-2/Ti6Al4V samples. On the other hand, compressive stress was found in the clad of Al₂O₃-1/Ti6Al4V sample. This phenomena was explained based on the thermal expansion coefficient.

7.1 Model set up

7.1.1 3D geometry and mesh

In this model, geometry and mesh were adopted from this thesis used in section 6.1.1. The dimension of substrate was 5 mm width, 3 mm height and 16 mm long. The clad height, width and length were 0.5 mm, 1.2 mm and 16 mm respectively. The geometry is shown in Fig. 7.1. In meshing, half of the geometry was taken by considering the symmetry along the laser scanning direction. In this model, transitional mapped mesh technique was applied. Finer mesh was applied in the clad and the part of the substrate and rest of the substrate experienced coarser mesh. The mesh distribution in the 3D model is given in Fig. 7.2. The total number of elements and nodes are 121497 and 100900 respectively. The hexahedron element (solid 70) having 8 nodes with a single degree of freedom (temperature) at

each node was used for transient thermal analysis. Then transient thermal model was coupled with mechanical/structural analysis. In mechanical analysis, solid 185 element having three degrees of freedom at each node (translations in the nodal X, Y, and Z directions) was used. The addition of mass/powder on substrate was used by element birth and kill technique. Elements of clad was killed and deactivated before applying heat source. When the heat source was applied to the laser-scanned region, the deactivated elements were activated with the moving heat source. In order to achieve accurate results, mesh convergence was done which is given in section 6.1.1 in detail.

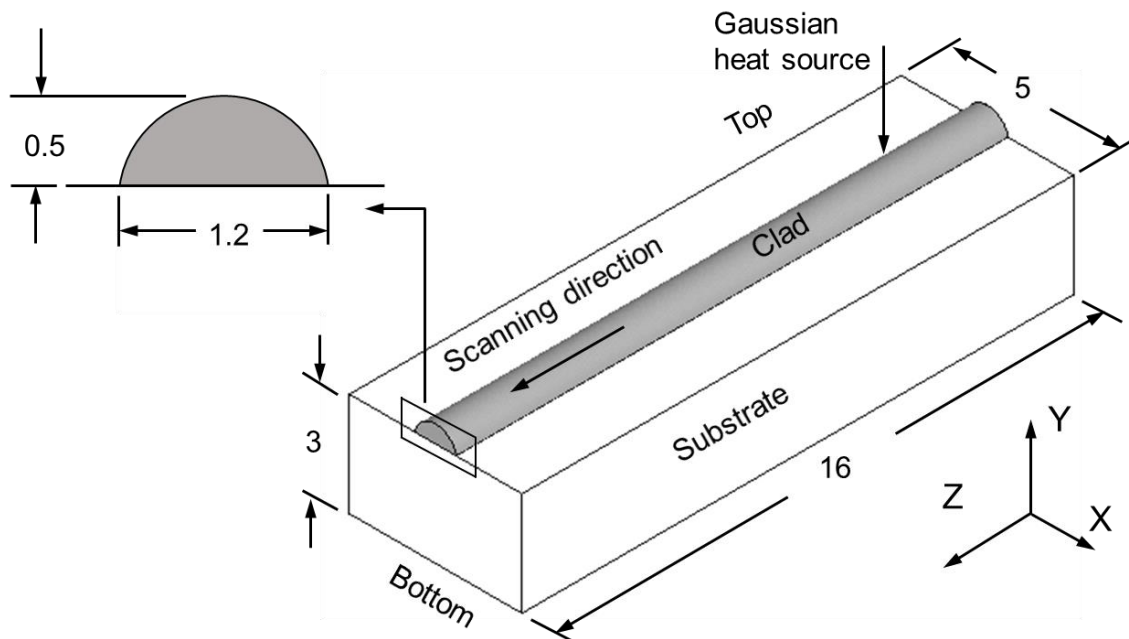


Fig. 7.1 The geometry of 3D model. All dimensions are in mm.

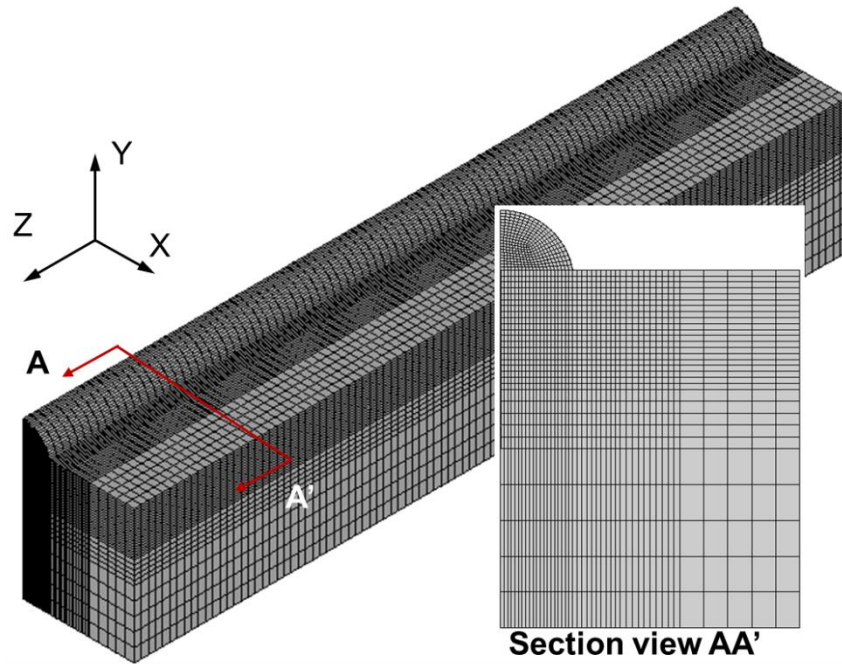


Fig. 7.2 The meshing of the 3D symmetry model.

7.1.2 Materials properties

Three different cladding materials (Al_2O_3 -1, Al_2O_3 -2 and TiC) were deposited on the surface of Ti6Al4V substrate material. In this work, two different types of Al_2O_3 have been used. The Al_2O_3 -1 is a refractory oxide and properties of this material were taken from AZO materials. On the other hand Al_2O_3 -2 is α -alumina which was produced by sintering. The properties of both alumina are different as their production process was different. Also, temperature independent properties were used for Al_2O_3 -1 where temperature dependent properties of Al_2O_3 -2 were used. For Al_2O_3 -1 and TiC, temperature independent material properties were used as temperature dependent material properties were not available. The used temperature independent material properties of Al_2O_3 -1 and TiC are given in Table 7.1. For Al_2O_3 -2, temperature dependent material properties were used as it was available in the literature. The temperature dependent thermal properties and

mechanical properties of Al₂O₃-2 are given in Fig. 7.3 and Fig. 7.4 respectively [184]. In this work, three clad materials samples were named as Al₂O₃-1/Ti6Al4V, Al₂O₃-2/Ti6Al4V and TiC/Ti6Al4V. For Ti6Al4V, temperature dependent material properties were used as mentioned in section 6.1.

Table 7.1 Thermo-mechanical properties of Al₂O₃-1 [174] and TiC [185] materials.

	Property	Units	Al ₂ O ₃ -1	TiC
Thermal material properties	Density	kg/m ³	3980	4940
	Specific Heat	J/kg-K	955	781.66
	Thermal conductivity	W/m-K	38.5	30.93
	Thermal expansion coefficient	× 10 ⁻⁶ 1/K	10.9	7.7
	Melting temperature	K	2369	3338
Mechanical material properties	Young's modulus	GPa	413	451
	Poisson's ratio	-	0.33	0.19

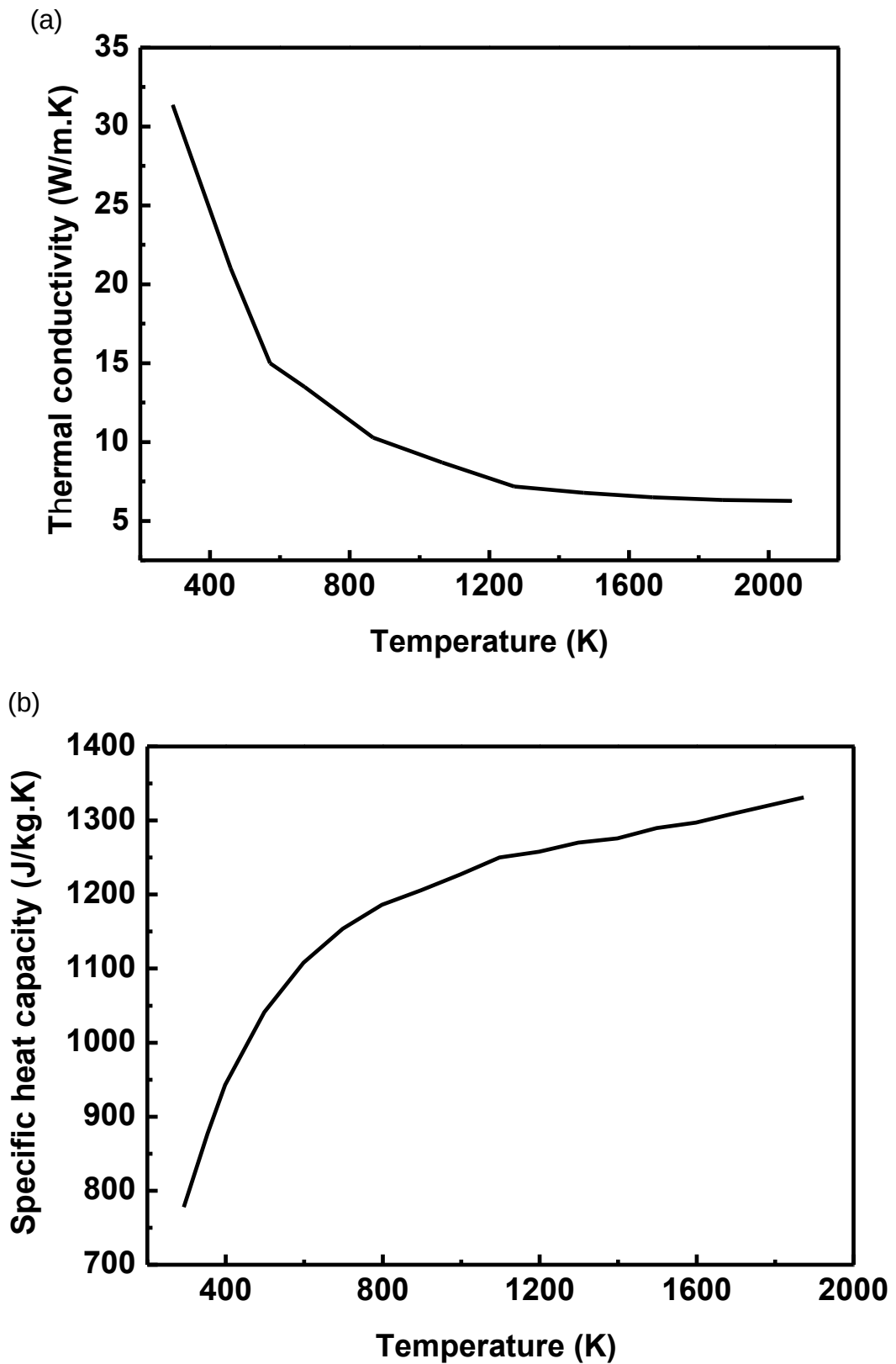


Fig. 7.3 Temperature dependent thermal properties of Al_2O_3 -2 (a) thermal conductivity and (b) specific heat capacity.

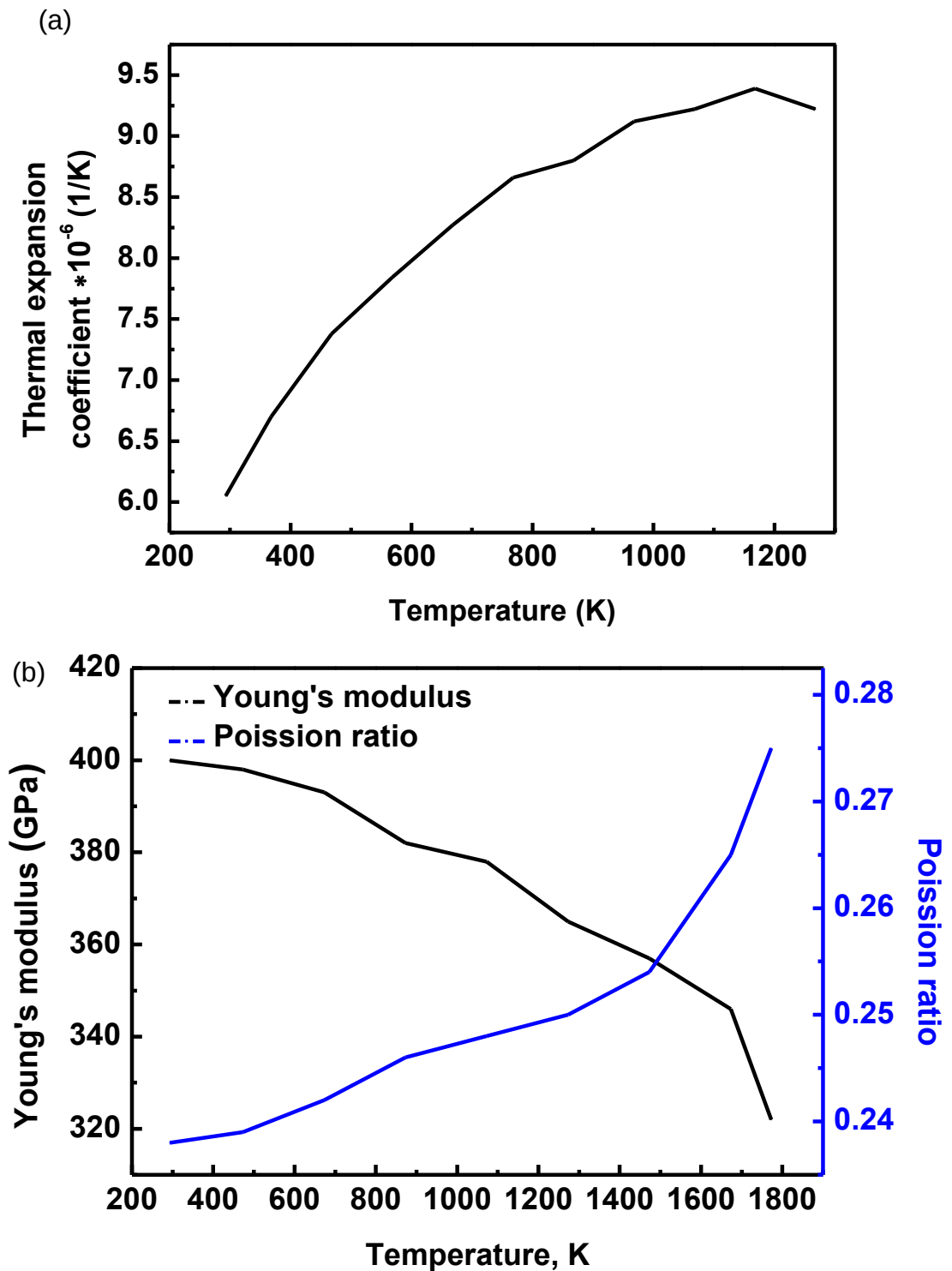


Fig. 7.4 Temperature dependent mechanical properties of of $\text{Al}_2\text{O}_3\text{-2}$ (a) thermal expansion coefficient and (b) Young's modulus and poisson ratio.

7.2 Laser parameters

The applied heat density mainly depends on two parameters: laser power and material absorptivity, see Eq. C6 in appendix C. However, material absorptivity depends on the wavelength of laser. For examples, the absorptivity of Ti6Al4V, Al₂O₃ and TiC are 0.25, 0.03 and 0.82 respectively for fiber laser which wavelength is around 1.06 μm . On the other hand, the absorptivity for CO₂ laser are 0.96 and 0.46 of Al₂O₃ and TiC respectively. Based on the absorptivity of materials, different level of power is required to achieve the same heat density, see Table 7.2. For example, the melting of Al₂O₃ with fiber laser will take very high power (~8000 W) which is very difficult to achieve where

The used fiber laser power is 250 W having 2 mm beam diameter. For Al₂O₃ and TiC deposited samples, laser power were optimized based on absorptivity under different wavelength lasers, given in Table 7.2

Table 7.2 Laser parameters for deposition of Al₂O₃-1/Ti6Al4V and TiC/Ti6Al4V samples.

Laser Parameters	Units	Laser type	Al ₂ O ₃	TiC
Laser power	W	Fiber	8000	380
		CO ₂	250	675
Laser travel speed	mm/s	-	700	700
Beam diameter	mm	-	1	1
Absorption coefficient	-	Fiber	0.03	0.82
		CO ₂	0.96	0.46

7.3 Results and discussion

7.3.1 Optimization of process parameters

In order to develop Al_2O_3 -1/Ti6Al4V and TiC/Ti6Al4V model, laser scanning speed (700 mm/min) and beam radius (1 mm) were fixed and laser power was optimised. Laser power was optimised based on the peak temperature and the temperature at the end of the clad. At 250 W laser power, the temperature at the end of Al_2O_3 -1 reached above the melting temperature (2369 K) which ensures the proper melting of the entire clad material. For TiC/Ti6Al4V sample, the optimised laser power was 380 W. Later same laser power of Al_2O_3 -1/Ti6Al4V model was used to develop Al_2O_3 -2/Ti6Al4V model. The optimised laser powers are given in Table 7.3.

Table 7.3 Optimisation of laser power for Al_2O_3 -1/Ti6Al4V and TiC/Ti6Al4V samples.

Al_2O_3-1/Ti6Al4V			
Power (W)	Beam radius (mm)	Peak temperature (K)	Temperature at the clad end (K)
200	0.001	2555	2019
225	0.001	2828	2225
250	0.001	3101	2468
TiC/Ti6Al4V			
300	0.001	3162	2781
380	0.001	3911	3428
400	0.001	4098	3589
500	0.001	5029	4393

7.3.2 Temperature distribution

Fig. 7.5 shows the temperature evolution at the interface of the clad and the substrate in the middle location of the sample during the laser cladding process for

Al_2O_3 -1/Ti6Al4V and TiC/Ti6Al4V samples. The predicted temperature profile offers the formation time of the melt pool and peak temperature at the interface of the clad and the substrate. The peak temperature at the interface were 3170 K and 4082 K

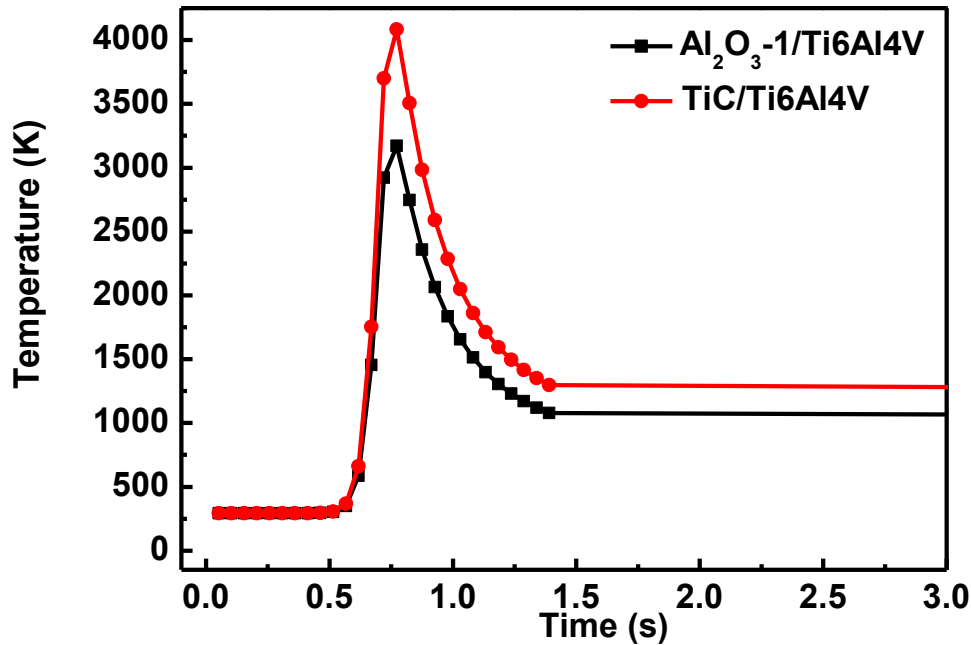


Fig. 7.5 The transient temperature distribution of Al_2O_3 -1/Ti6Al4V and TiC/Ti6Al4V samples

for Al_2O_3 -1/Ti6Al4V and TiC/Ti6Al4V samples respectively. In both cases, the peak temperatures were above the melting temperature which ensured of melting of clad material.

Heating and cooling cycle shown in Fig. 7.6. The maximum heating rate was 2.3×10^4 K/s and the maximum cooling rate was 6.6×10^3 K/s for Al_2O_3 -1/Ti6Al4V sample. The predicted maximum heating rate and cooling rate of TiC/Ti6Al4V sample were 2.9×10^4 K/s and 1.1×10^4 K/s respectively. From the cooling rate, the microstructure can be predicted after solidification for ceramics material.

Ceramics-based laser additive manufacturing is a complex process. The solidification mechanism and microstructural evolution are currently not fully understood. Recently, the solidification mechanism and phase formation of

ceramics materials have been focused in the selective laser melting process. In this process, the predicted cooling rate during deposition of Al_2O_3 was 7.038×10^3 K/s results columnar and equiaxial dendrites microstructure [186]. The predicted cooling rate of Al_2O_3 -1/Ti6Al4V sample was 6.6×10^3 K/s which was near to the cooling rate proposed by Fan et al. [186]. Therefore, we can assume the microstructure in this system will be columnar and equiaxial dendrites in the Al_2O_3 clad. In the Ti6Al4V substrate, the cooling rate was 6.6×10^3 K/s which can form of α' martensite in the melt pool. The material in HAZ reaches above the β transus temperature (1267 K) and results fine Widmanstatten structure [179]. Finally, the location which is below martensitic transformation temperature (~ 1073 K) will have the same micro-structure of primary substrate phase. The predicted cooling rate of TiC/Ti6Al4V sample was 1.1×10^4 K/s. S. Liu et al. reported that the predicted cooling rate 10^4 K/s of TiC produced dendritic structure in the laser selective melting process [187]. In the current work, the cooling rate is almost same as the reported cooling rate by S. Liu et al. which ensures the formation of dendritic structure in the clad. In substrate material, the micro-structure will be same as the sample in Al_2O_3 -1/Ti6Al4V.

The height of the clad, melt pool and HAZ of Al_2O_3 -1/Ti6Al4V and TiC/Ti6Al4V samples are shown in Fig. 7.7. The clad zone is the deposited material. The melt pool height is defined where the material is higher the liquidus temperature. The material in HAZ reaches above the β transus temperature (1267 K) [179]. Finally, the location which is below martensitic transformation temperature (~ 1073 K) will have the same micro-structure of primary substrate phase. In case of Al_2O_3 -1/Ti6Al4V sample, the height of the clad, melt pool and HAZ were 0.5 mm, 0.725 mm and 0.35 mm respectively. The melt pool (0.85 mm) and HAZ (0.38 mm) of the

TiC/Ti6Al4V sample were higher than the Al_2O_3 -1/Ti6Al4V sample as the Al_2O_3 had lower peak temperature than TiC samples.

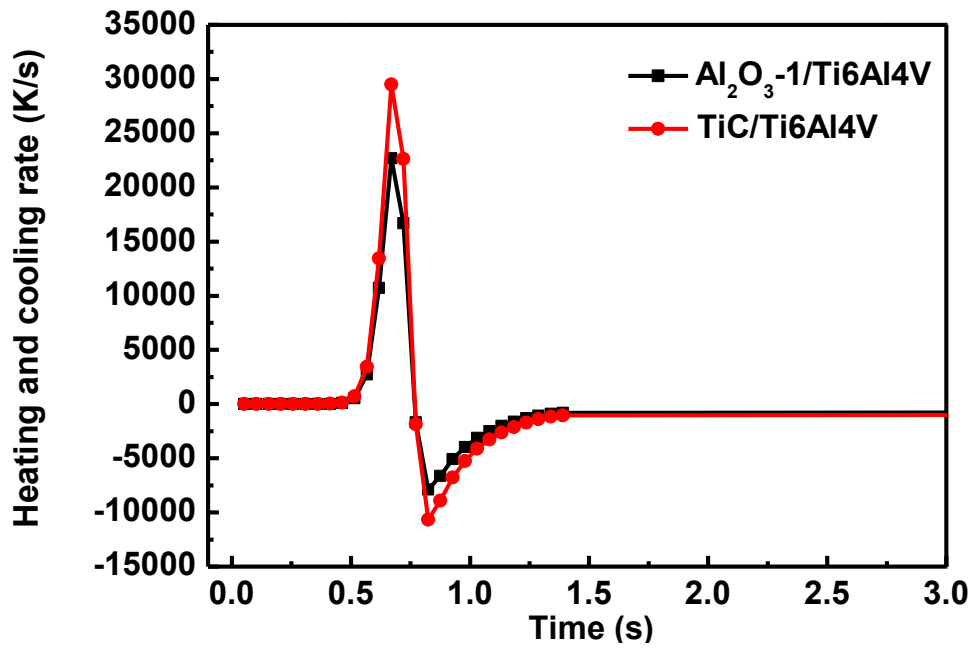


Fig. 7.6 Heating and cooling cycles of Al_2O_3 -1/Ti6Al4V and TiC/Ti6Al4V samples.

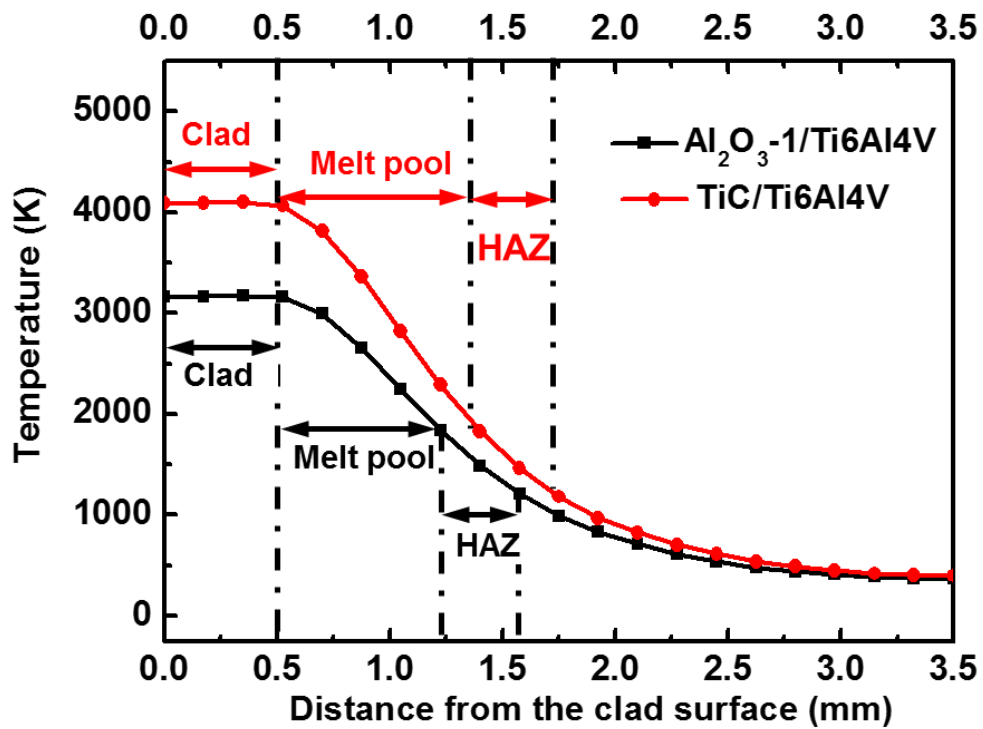


Fig. 7.7 The temperature distribution from the clad surface to the bottom of the substrate of Al_2O_3 -1/Ti6Al4V and TiC/Ti6Al4V samples.

7.3.3 Residual stress distribution

Fig. 7.8 shows the residual stresses distribution of Al_2O_3 -1/Ti6Al4V sample at the path MN. In the clad, the predicted residual stresses in X and Z directions along the path MN were mainly tensile in nature. The maximum tensile residual stress (~ 70 MPa) in X direction was found at the top of the clad which turns to compressive after 0.525 mm in the substrate material. In Z direction, around 47 MPa tensile residual stress was found at the top of the clad and decreased towards the substrate. In Y direction, always compressive stress was found due to the application of boundary constrain in Y direction. The maximum equivalent von Mises stress was around 80 MPa.

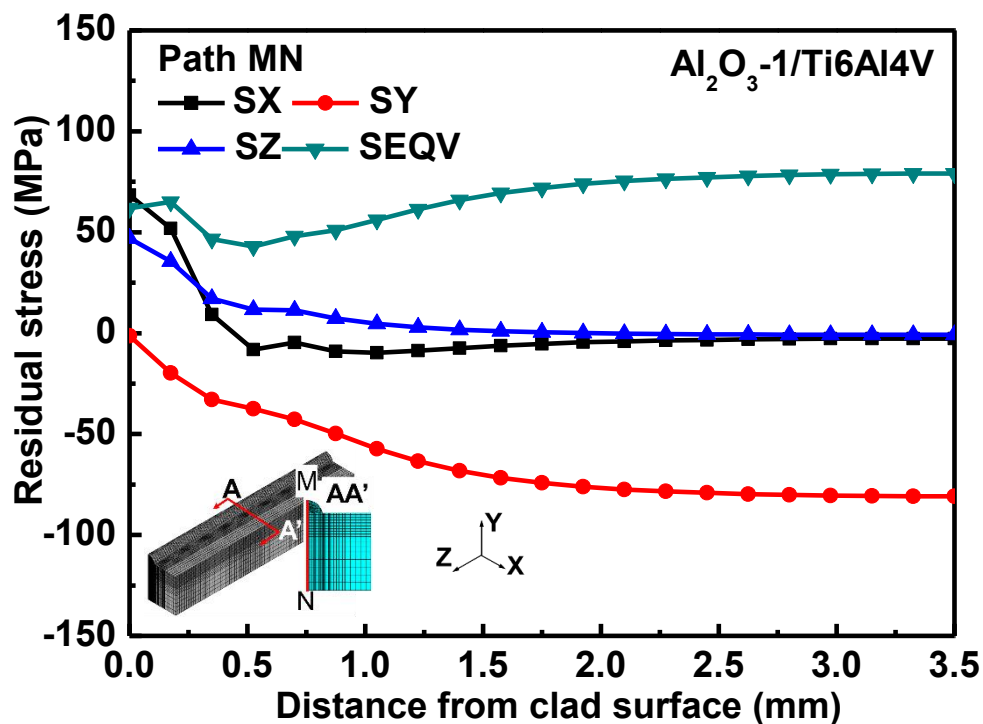


Fig. 7.8 The residual stresses distribution of Al_2O_3 -1/Ti6Al4V along the path MN.

The predicted residual stresses in path OP of Al_2O_3 -1/Ti6Al4V sample are shown in Fig. 7.9. In this path, tensile residual stress was formed in Z direction. Maximum tensile residual stress was found at the end of the clad around 20 MPa. In both X and Y directions, compressive stresses were found throughout the clad and substrate material. The predicted von-Mises stress (SEQV) (~205 MPa) was lower than the yield stress of Ti6Al4V (1061 MPa [178]) and the tensile strength of Al_2O_3 (665 MPa [174]).

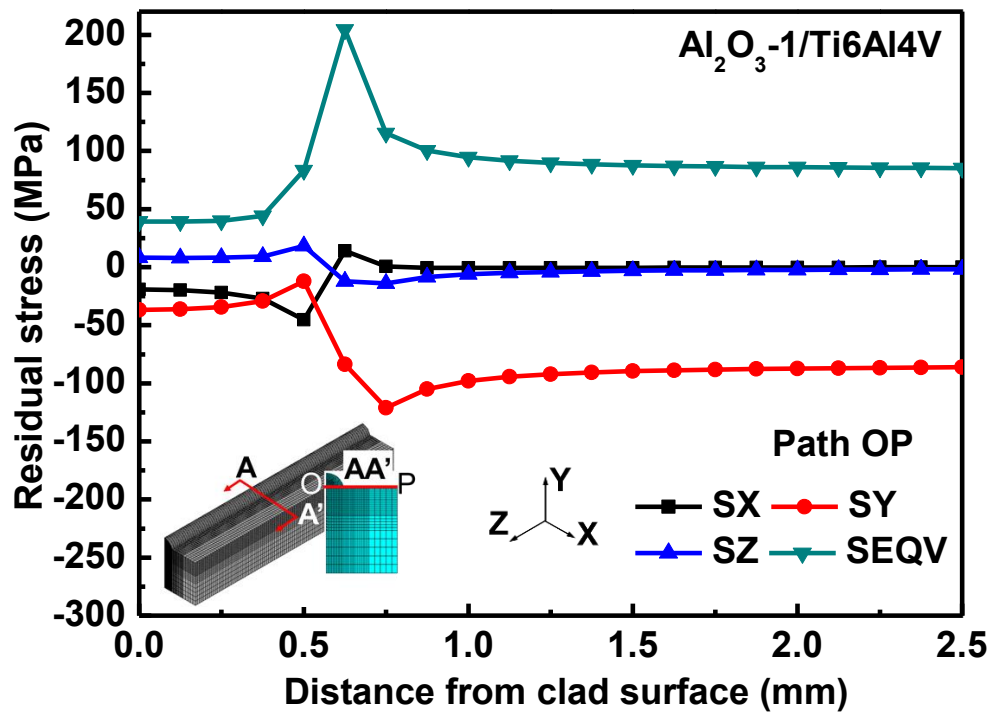


Fig. 7.9 The residual stresses distribution of Al_2O_3 -1/Ti6Al4V along the path OP.

Fig. 7.10 shows the residual stresses distribution of TiC/Ti6Al4V sample at the path MN. In the clad, the predicted residual stresses in X and Z directions along the path MN are mainly tensile in nature. In X direction, maximum stress at the top of the clad is around 60 MPa and then turned to compressive stress in the substrate. In Z direction, 160 MPa was formed at the top of the clad and decreased to the interface

of the clad and turned to compressive in the substrate. The predicted maximum equivalent von-Mises stress (SEQV) was ~160 MPa.

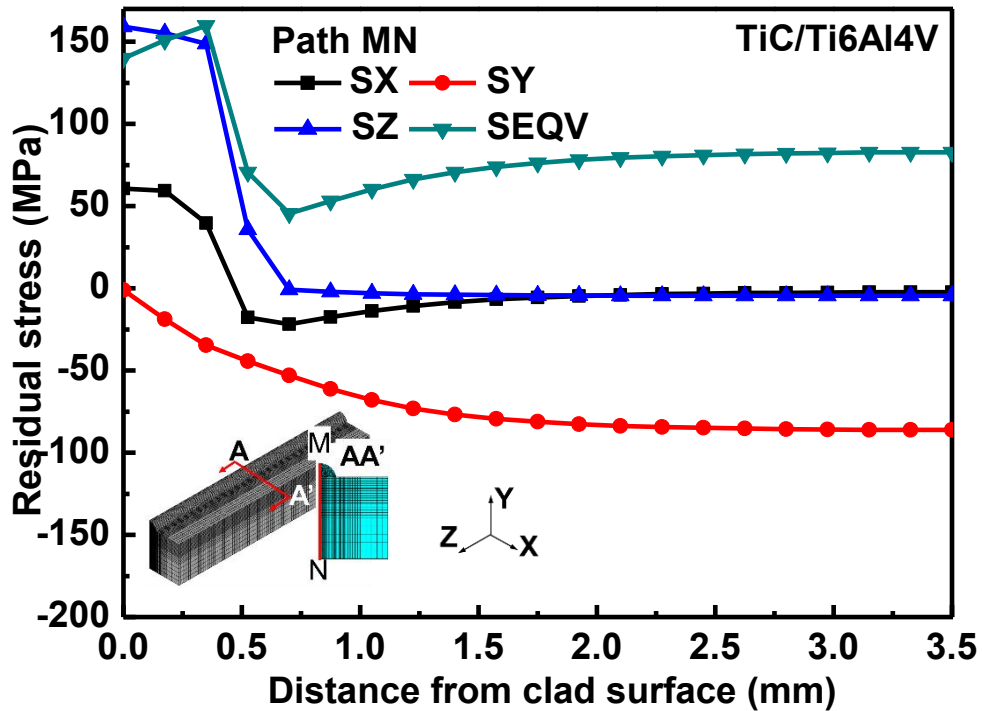


Fig. 7.10 The residual stresses distribution of TiC/Ti6Al4V along the path MN.

The predicted residual stresses in path OP of TiC/Ti6Al4V sample are shown in Fig. 7.11. In this path, tensile residual stress was formed in Z direction. Maximum tensile residual stress was found at the end of the clad around 86 MPa. In X direction, compressive stress was found throughout the clad and turned to tensile in the substrate material. In Y direction, compressive stresses were found throughout the clad and substrate material. The predicted von-Mises stress (~274 MPa) was lower than the yield stress of Ti6Al4V (1061 MPa [178]) and slightly higher than the tensile strength of TiC (258 MPa [167]).

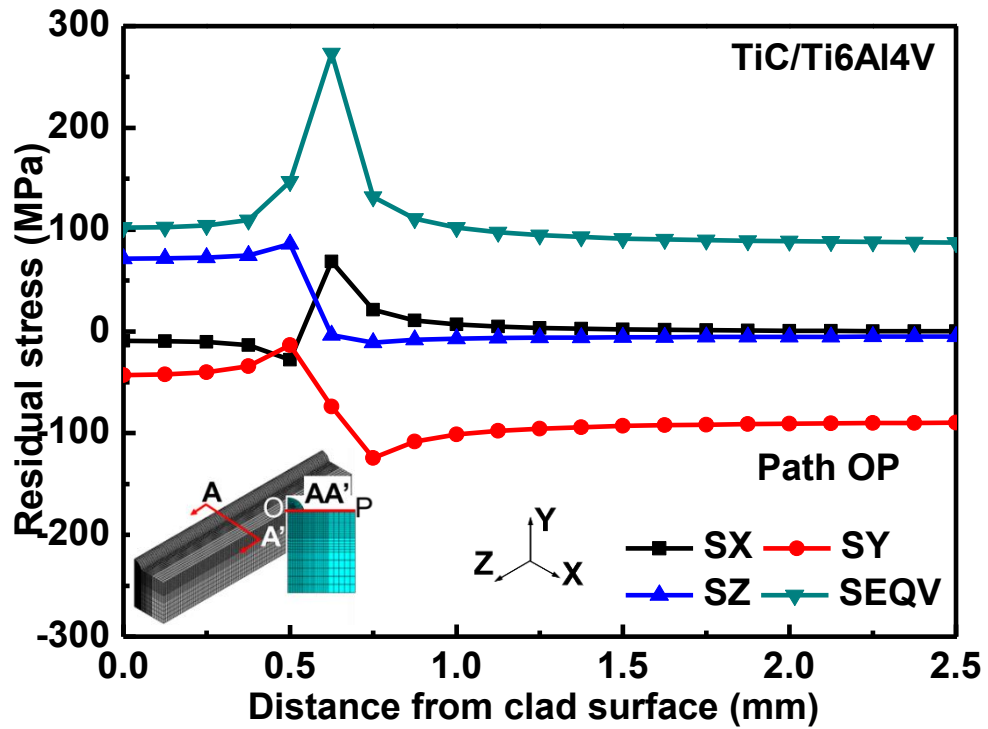


Fig. 7.11 The residual stresses distribution of TiC/Ti6Al4V along the path OP.

Both $\text{Al}_2\text{O}_3\text{-1/Ti6Al4V}$ and TiC/Ti6Al4V samples showed tensile stresses in the clad in both X and Z directions. However, TiC/Ti6Al4V sample showed higher tensile residual stress in Z directions and von Mises equivalent stress than $\text{Al}_2\text{O}_3\text{-1/Ti6Al4V}$ sample. The reason of formation of higher tensile residual stresses in TiC/Ti6Al4V sample is the higher elastic strain in the clad than $\text{Al}_2\text{O}_3\text{-1/Ti6Al4V}$ as TiC has higher Young's modulus than $\text{Al}_2\text{O}_3\text{-1}$.

7.3.4 Effect of temperature dependant material properties of Al_2O_3

Al_2O_3 -1 and Al_2O_3 -2 are the refractory alumina and α -alumina respectively. For Al_2O_3 -1, temperature independent material properties were applied. On the other hand, temperature dependent material properties were applied for Al_2O_3 -2. In both cases, temperature distribution and residual stress distribution have been predicted. Fig. 7.12 shows the transient temperature distribution of Al_2O_3 -1/Ti6Al4V and Al_2O_3 -2/Ti6Al4V samples at the interface of the clad and the substrate. Similar temperature distribution was found for both cases.

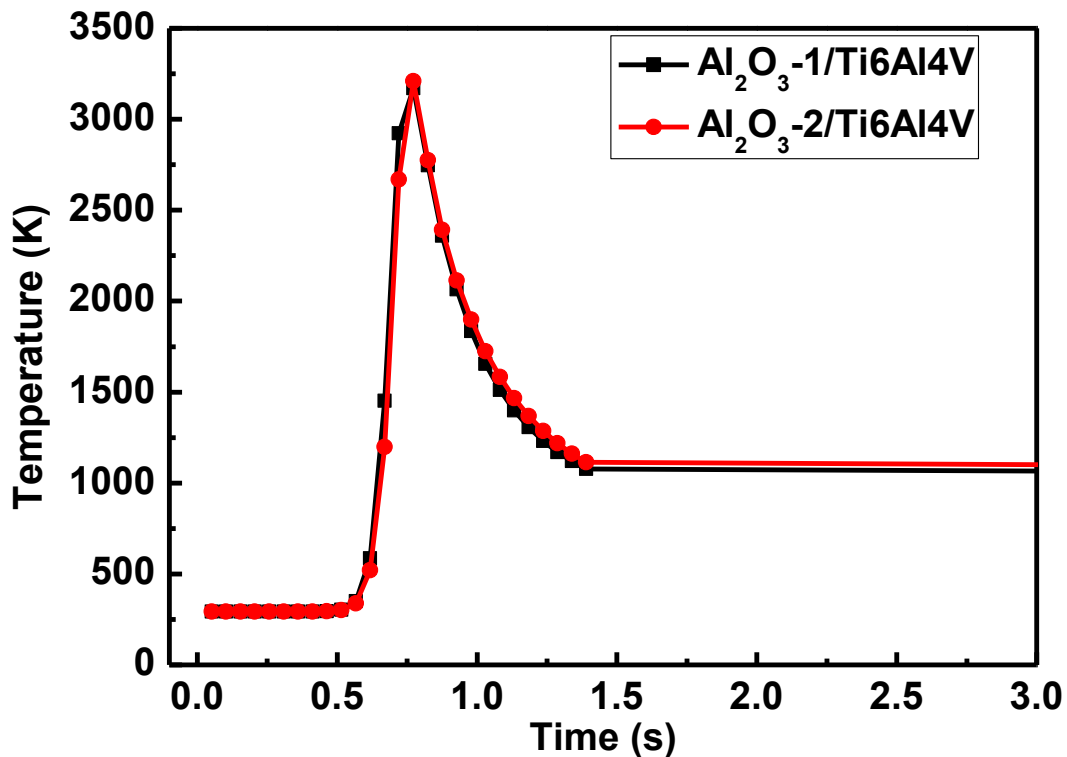


Fig. 7.12 Temperature distribution of Al_2O_3 -1/Ti6Al4V and Al_2O_3 -2/Ti6Al4V samples.

The residual stress distribution of for Al_2O_3 -1/Ti6Al4V and Al_2O_3 -2/Ti6Al4V samples along the path MN are given in Fig. 7.13. In both samples, tensile residual stresses were found in the clad in both X and Z directions. In X direction, the maximum tensile residual stress in Al_2O_3 -1/Ti6Al4V was ~ 69 MPa where ~ 56 MPa was found in

Al₂O₃-2/Ti6Al4V sample. However, in Z direction, Al₂O₃-2/Ti6Al4V sample produced higher tensile residual stress (~ 199 MPa) than Al₂O₃-1/Ti6Al4V sample (~ 47 MPa). The von Mises equivalent stress was also higher in Al₂O₃-2/Ti6Al4V sample (~ 200 MPa) than Al₂O₃-1/Ti6Al4V sample (~ 80 MPa).

Fig. 7.14 shows the residual stresses distribution of Al₂O₃-1/Ti6Al4V and Al₂O₃-2/Ti6Al4V samples along the path OP. In Z direction, both Al₂O₃-1/Ti6Al4V and Al₂O₃-2/Ti6Al4V samples showed tensile residual stresses in the clad. Al₂O₃-2/Ti6Al4V sample generated higher tensile residual stress (107 MPa) than Al₂O₃-1/Ti6Al4V sample (18 MPa). The von Mises equivalent stress was also higher in Al₂O₃-2/Ti6Al4V sample (~ 294 MPa) than Al₂O₃-1/Ti6Al4V sample (~ 204 MPa).

It is reported by Zhu et al. that higher residual stresses were generated in the welding joint for using temperature dependant thermal conductivity, Young's modulus and thermal expansion coefficient and yield stress than room temperature properties [188]. Because temperature dependent properties changes with temperature and affect the evolution of both thermal and elastic strain in the component [189]. Simulation of Al₂O₃-2/Ti6Al4V sample was performed using temperature dependant properties which generated higher residual stresses in the clad than Al₂O₃-1/Ti6Al4V sample.

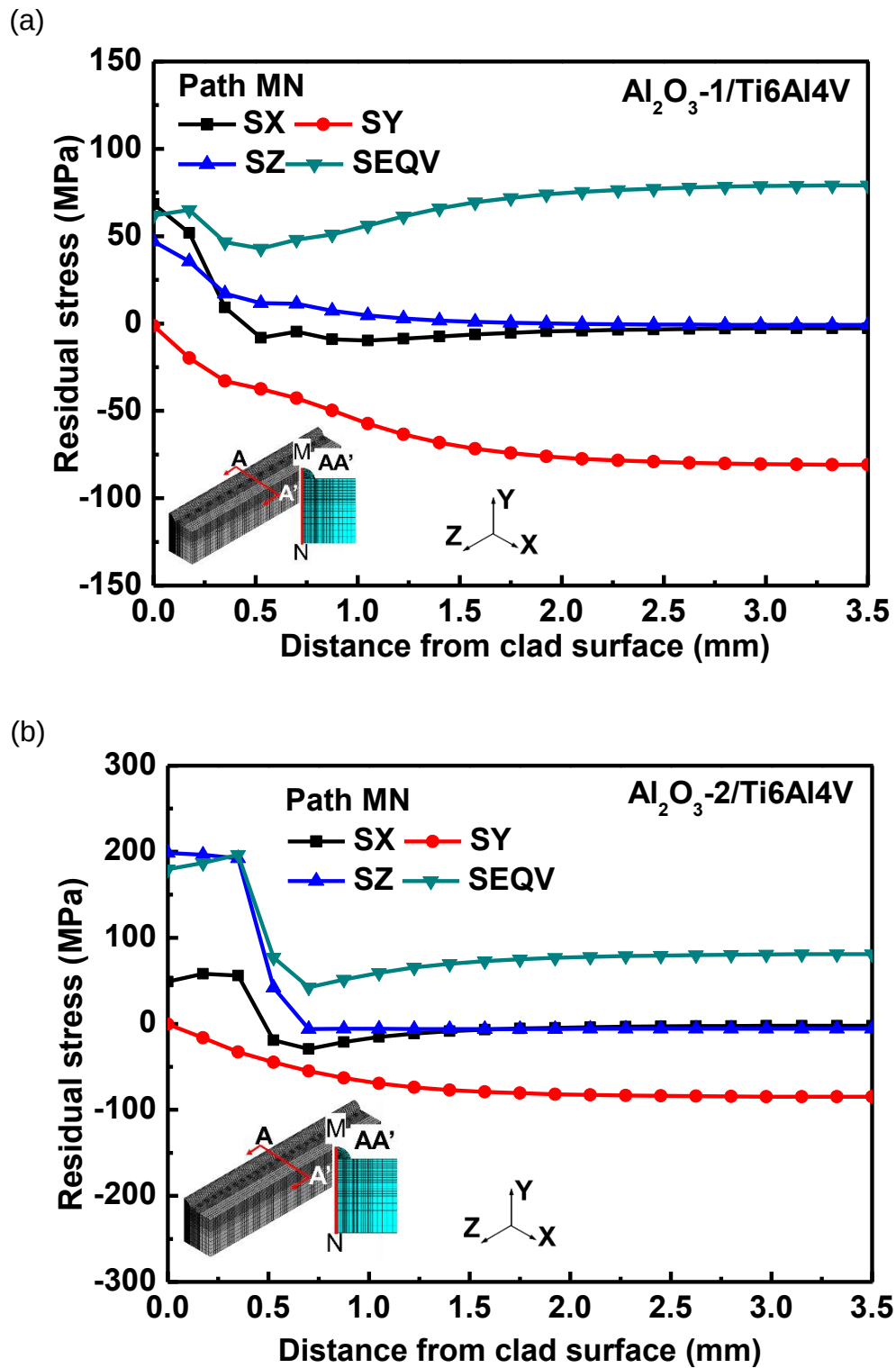
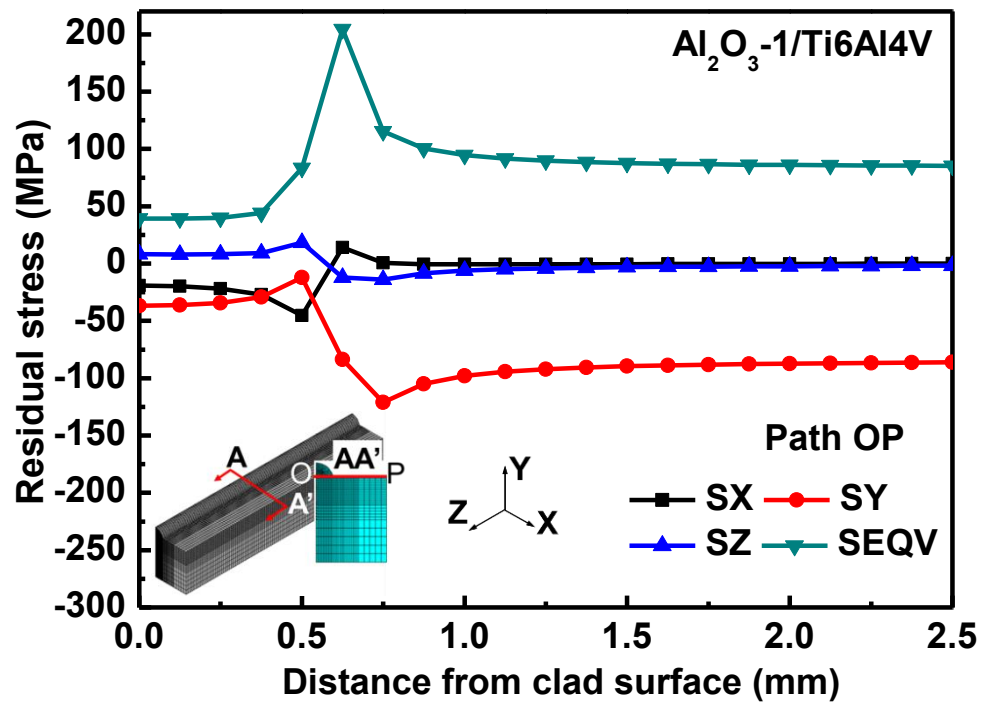


Fig. 7.13 The residual stresses distribution of $\text{Al}_2\text{O}_3\text{-1/Ti6Al4V}$ and $\text{Al}_2\text{O}_3\text{-2/Ti6Al4V}$ samples along the path MN.

(a)



(b)

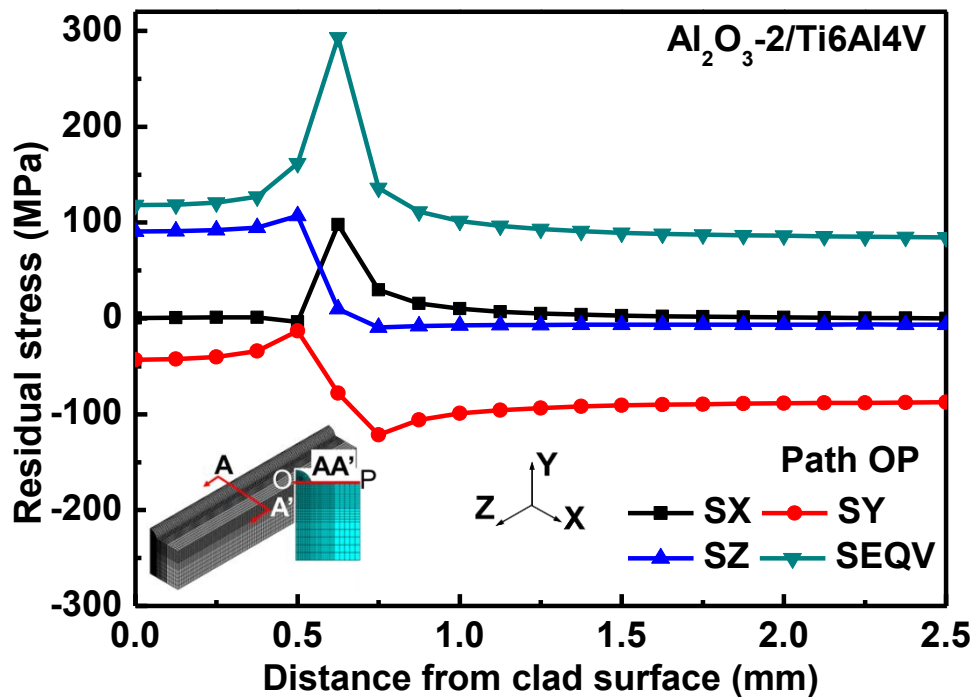


Fig. 7.14 The residual stresses distribution of Al₂O₃-1/Ti6Al4V and Al₂O₃-2/Ti6Al4V samples along the path OP.

7.4 Conclusion

3D thermo-mechanical model has been developed to predict the transient temperature distribution and the residual stress distribution for dissimilar clad and substrate material. The optimised laser power for Al_2O_3 -1/Ti6Al4V and TiC/Ti6Al4V samples were 250 W and 380 W respectively. The peak temperature at the interface for Al_2O_3 -1/Ti6Al4V and TiC/Ti6Al4V samples were 3101 K and 3911 K respectively. The predicted peak temperature was above the melting point of Al_2O_3 (2369 K) and TiC (3338 K) which ensured the proper melting of the entire clad material and the formation of metallurgical bonding with the substrate material. The predicted cooling rate of Al_2O_3 -1/Ti6Al4V sample was 6.6×10^3 K/s could claim the formation of columnar and equiaxial dendrites microstructure in the clad. For TiC/Ti6Al4V sample, 1.1×10^4 K/s cooling rate was found which also could claim the formation of dendritic structure in the clad. The predicted melt pool depth (0.725 mm) and HAZ (0.35 mm) of Al_2O_3 -1/Ti6Al4V sample were lower than the melt pool depth (0.85 mm) and HAZ (0.38 mm) of TiC/Ti6Al4V sample. Tensile residual stresses in Z direction of TiC/Ti6Al4V sample (160 MPa) was higher than Al_2O_3 -1/Ti6Al4V sample (47 MPa). The maximum predicted equivalent stress (SEQV) in TiC/Ti6Al4V sample (274 MPa) was higher than Al_2O_3 -1/Ti6Al4V sample (205 MPa). Furthermore, both Al_2O_3 -1 (the refractory alumina) and Al_2O_3 -2 (α -alumina) generated tensile residual stresses on the same substrate, Ti6Al4V. However, due to temperature dependant properties, Al_2O_3 -2/Ti6Al4V sample generated higher tensile residual stresses than Al_2O_3 -1/Ti6Al4V.

8 Summary and future work

8.1 Summary

Conceptual, analytical and numerical models have been done to predict residual stresses in the laser cladding process. In conceptual model, a simple physical model of Laser Cladding process has been presented to discuss the effect of temperature on strain and stress in different location during the Laser Cladding process. The magnitude of temperature, heating rate and cooling rate in the clad material were higher than in the substrate material. From the clad top surface to substrate at near interface, tensile strain and stresses were found. During heating, compressive stress was formed near the interface of substrate which turned to tensile stress at the end of cooling. In order to get quantitative value of residual stresses, analytical model has been done.

An analytical model has been used to predict and compare stresses in dissimilar clad and substrate materials system with a range of preheating temperature of the substrate. Four cladding materials TiO_2 , TiC , ZrO_2 and Al_2O_3 were used on the H13 steel substrate. The minimum residual stress was found for Al_2O_3 clad on the H13 steel substrate. Below 900 K preheating temperature of the substrate, maximum residual stress was generated in the TiC clad. The maximum residual stress formed in ZrO_2 clad above 900 K. Six cladding materials (Al_2O_3 , TiC , TiO_2 , ZrO_2 , SiC and TiN) on the Ti6Al4V substrate at a range of preheating temperature (300 K to 1200 K) of the substrate were investigated. TiN cladding material generated the maximum tensile residual stress on the Ti6Al4V substrate. Below 1000 K, Al_2O_3 generated higher residual stress than SiC and at 1000 K, SiC and Al_2O_3 generated almost same residual stress. The thermal strain and Young's modulus were found as key reasons of the generation and control of residual stresses. This analysis can be used to find a combination of materials that can generate minimum residual stress.

This model is capable to include preheating temperature of the substrate and predict its effect on the distribution of the residual stress. The increment of preheating temperature of substrate decreased the residual stress. In this model, temperature independent material properties have been used. This model is limited to use the effect of temperature dependent material properties. Moreover, this model cannot predict the generation of stresses in more than one dimension. Furthermore, this model was restricted to melting temperature of the clad material. However, in practical scenario, surface of the substrate material also reach to melting temperature by laser heat source which cannot be included here. These limitations have been removed by applying numerical method in the Laser Cladding process in next chapters.

2D thermo-mechanical model has been developed to predict temperature distribution and residual stresses distribution of Laser Cladding process for deposition of H13 steel, Al_2O_3 and TiC cladding materials on the H13 substrate material. From temperature distribution, it was found that all cladding materials went above the melting temperature at the interface. TiC coating formed higher temperature gradient because of its highest peak temperature. The predicted maximum equivalent residual stress of H13/H13, Al_2O_3 /H13 and TiC/H13 samples were 794 MPa, 1220 MPa and 1359 MPa in the middle of the clad respectively. The generated residual stress of Al_2O_3 /H13 sample was lower than the TiC/H13 samples due as the total strain was lower between Al_2O_3 and H13. It can be claimed that the deposition of H13 clad material could be appropriate for repair application as the generated stress is far below than the yield stress of H13 steel (1650 MPa). However, deposition of Al_2O_3 and TiC deposition could form cracks in the clad.

3D thermo-mechanical model based on finite element method has been developed to determine the temperature distribution and residual stresses. In this model, Ti6Al4V clad material was deposited on the surface of Ti6Al4V substrate. In order to develop this model, benchmarking has been done to verify the accuracy of the mesh and boundary conditions. The difference of peak temperature and melt pool depth between the current model and established model were 1.9% and 0.97% respectively, which was good enough to predict further results. The optimised laser power, beam diameter and scanning speed of this current model were 600 W, 1.4 mm and 700 mm/s respectively. From temperature profile, the peak temperature at the interface (3201 K), shape and distribution of heat in clad and the substrate, depth of melt pool (0.5 mm) and HAZ (0.23 mm), the formation time of melt pool, maximum heating rate (2.45×10^4 K/s) and cooling rate (1.1×10^4 K/s) were extracted. From cooling rate, micro-structure in the clad, melt pool and HAZ were predicted. Material in the clad and melt pool generated the acicular α' martensite as the material experienced high cooling rate (1.1×10^4 K/s) and the temperature was above the liquidus temperature (1941 K). The material in HAZ reached above the β transus temperature (1267 K) and experienced medium to slow cooling rate which resulted combination of acicular α' martensite fine Widmanstätten structure. Finally, material which was below martensitic transformation temperature (~ 1073 K) will have the same micro-structure of primary substrate phase before heat treatment. Tensile residual stresses were found in the clad and near substrate. Maximum tensile stress was 108 MPa which is far below the yield strength (1100 MPa) of Ti6Al4V material. 3D thermo-mechanical model has been extended to predict the transient temperature distribution and the residual stress distribution for dissimilar clad and substrate material. In these models, Al₂O₃-1, Al₂O₃-2 and TiC cladding material were

deposited on the surface of Ti6Al4V material. The optimised laser power for Al₂O₃-1/Ti6Al4V and TiC/Ti6Al4V samples were 250 W and 380 W respectively. The peak temperature at the interface for Al₂O₃-1/Ti6Al4V and TiC/Ti6Al4V samples were 3101 K and 3911 K respectively. The predicted peak temperature was above the melting point of Al₂O₃ (2369 K) and TiC (3338 K) which ensured the proper melting of the entire clad material and the formation of metallurgical bonding with the substrate material. The predicted cooling rate of Al₂O₃-1/Ti6Al4V sample was 6.6×10³ K/s could claim the formation of columnar and equiaxial dendrites microstructure in the clad. For TiC/Ti6Al4V sample, 1.1×10⁴ K/s cooling rate was found which also could claim the formation of dendritic structure in the clad. The predicted melt pool depth (0.725 mm) and HAZ (0.35 mm) of Al₂O₃-1/Ti6Al4V sample were lower than the melt pool depth (0.85 mm) and HAZ (0.38 mm) of TiC/Ti6Al4V sample. Tensile residual stresses in Z direction of TiC/Ti6Al4V sample (160 MPa) was higher than Al₂O₃-1/Ti6Al4V sample (47 MPa). The maximum predicted equivalent stress (SEQV) in TiC/Ti6Al4V sample (274 MPa) was higher than Al₂O₃-1/Ti6Al4V sample (205 MPa). Furthermore, both Al₂O₃-1 (the refractory alumina) and Al₂O₃-2 (α-alumina) generated tensile residual stresses on the same substrate, Ti6Al4V. However, due to temperature dependant properties, Al₂O₃-2/Ti6Al4V sample generated higher tensile residual stresses than Al₂O₃-1/Ti6Al4V.

8.2 Future work

All the research works and results presented in this dissertation are considered as a small part of the current global research on the Laser Cladding process. Further research which could be considered doing in future are

1. Optimisation of process parameters and prediction of residual stresses of multi-layer and multi-pass deposition in Laser Cladding process. In order to do this, a model consists of multi-layer clad need to be produced. Then transitional mesh could be applied in the model to perform thermo-mechanical model. To run this model, high performance computer is required as the number of calculation is very high. Additionally, the effect of scanning speed and scanning direction on multi-layer and multi-pass deposition need to be investigated.
2. Development of a single model including the prediction of temperature distribution, melt pool flow and properties of clad. In order to perform this single model, a direct coupling of thermal model with fluid dynamic model and structural model is required. Heat source model needs to be modified based on the shape of melt pool and heat affected zone (HAZ) to reduce the error in prediction of shape of the melt pool and HAZ. In addition, the post-processing actions (heat treatment, cutting, machining, and polishing) of the process can be included to optimize process parameters.
3. This model can be extended to predict other mechanical properties such as hardness and fatigue life in the laser clad component. Hardness can be calculated from the hardness value of various phases. All phases can be predicted from the temperature distribution. In this work, the developed model shows the ability to predict transient temperature distribution and microstructure in the Laser cladding process. So, this developed knowledge can be easily applied to predict

hardness in this process. Furthermore, the prediction of fatigue life could be performed by calculating stress intensity factor at the crack tip in the clad. The developed knowledge on finite element method, transient temperature distribution and residual stress distribution can be transferred to other process such as laser welding, selective laser melting and direct laser deposition process.

4. Hybrid technique such as addition of preheating of substrate using furnace and ultra sound vibration could be included in the simulation to reduce residual stress distribution. In order to add preheating effect, initial boundary condition need to be modified. Heating the substrate below and above the phase transformation temperature have significant effect on the microstructure. So, the effect of preheating of substrate on microstructure, residual stresses, hardness and fatigue life can be predicted through simulation. To add vibration, an additional mechanical vibrator could be added. The effect of preheating of substrate and addition of vibration could be optimised and compare for better mechanical properties in the clad and HAZ. In order to validate the models, experimental work could be run and validate the model with the collaboration of industries.

References

- [1] E. Toyserkani, A. Khajepour, S. F. Corbin, *Laser Cladding*, 1st ed., CRC Press, USA, 2004.
- [2] T. Torims, The application of Laser Cladding to mechanical component repair, renovation and regeneration, in: B. Katalinic, Z. Tekic (Eds.), *DAAAM Int. Sci. B.*, 1st ed., DAAAM International Publishing, Vienna, Austria, 2013: pp. 587–608. doi:10.2507/daaam.scibook.2013.32.
- [3] C. Leyens, E. Beyer, Innovations in laser cladding and direct laser metal deposition, in: J. Lawrence, D. Waugh (Eds.), *Laser Surf. Eng. Process. Appl.* 1st Ed., Woodhead Publishing, United Kingdom, 2014: pp. 181–192. doi:10.1016/B978-1-78242-074-3.00008-8.
- [4] A. Grueninger, M. Hustedt, D. Herzog, M. Huse, D. Kracht, H. Haferkamp, A. Ostendorf, Surface texturing by Laser Cladding, *J. Laser Appl.* 23 (2011) 22008. doi:10.2351/1.3573371.
- [5] Laser Cladding Offers Unique Advantages, (2013). <http://www.fabricatingandmetalworking.com/2013/12/laser-cladding-offers-unique-advantages/> (accessed January 21, 2019).
- [6] C. Cho, G. Zhao, S.Y. Kwak, C.B. Kim, Computational mechanics of laser cladding process, *J. Mater. Process. Technol.* 153–154 (2004) 494–500. doi:10.1016/j.jmatprotec.2004.04.016.
- [7] Global Laser Cladding Equipment Market - Drivers and Forecast from Technavio, (2017). <http://www.businesswire.com/news/home/20170223005577/en/Global-Laser-Cladding-Equipment-Market---Drivers%0A>.
- [8] A.J. Pinkerton, Advances in the modeling of laser direct metal deposition, *J. Laser Appl.* 27 (2015) S15001. doi:10.2351/1.4815992.
- [9] A.P. Mackwood, R.C. Crafer, Thermal modelling of laser welding and related processes: a literature review, *Opt. Laser Technol.* 37 (2005) 99–115. doi:10.1016/j.optlastec.2004.02.017.

- [10] Y. Chew, J.H.L. Pang, G. Bi, B. Song, Thermo-mechanical model for simulating laser cladding induced residual stresses with single and multiple clad beads, *J. Mater. Process. Technol.* 224 (2015) 89–101. doi:10.1016/j.jmatprotec.2015.04.031.
- [11] I.A. Roberts, Investigation of residual stresses in the Laser Melting of metal powders in additive layer, (2012).
- [12] M. Eslami, R. Hetnarski, J. Ignaczak, N. Noda, N. Sumi, Theory of elasticity and thermal stresses, 1st ed., Waterloo, Canada, 2013. <http://link.springer.com/content/pdf/10.1007/978-94-007-6356-2.pdf>.
- [13] S. Da Sun, Q. Liu, M. Brandt, V. Luzin, R. Cottam, M. Janardhana, G. Clark, Effect of laser clad repair on the fatigue behaviour of ultra-high strength AISI 4340 steel, *Mater. Sci. Eng. A.* 606 (2014) 46–57. doi:10.1016/j.msea.2014.03.077.
- [14] T. Gabriel, D. Rommel, F. Scherm, M. Gorywoda, U. Glatzel, Laser cladding of ultra-thin nickel-based superalloy sheets, *Materials (Basel)*. 10 (2017) 1–12. doi:10.3390/ma10030279.
- [15] Y. Sun, M. Hao, Statistical analysis and optimization of process parameters in Ti6Al4V laser cladding using Nd:YAG laser, *Opt. Lasers Eng.* 50 (2012) 985–995. doi:10.1016/j.optlaseng.2012.01.018.
- [16] Y. Lin, Y. Lei, X. Li, X. Zhi, H. Fu, A study of TiB₂/TiB gradient coating by laser cladding on titanium alloy, *Opt. Lasers Eng.* 82 (2016) 48–55. doi:10.1016/j.optlaseng.2016.01.016.
- [17] W. Wang, M. Wang, Z. Jie, F. Sun, D. Huang, Research on the microstructure and wear resistance of titanium alloy structural members repaired by laser cladding, *Opt. Lasers Eng.* 46 (2008) 810–816. doi:10.1016/j.optlaseng.2008.05.015.
- [18] J. Liu, H. Yu, C. Chen, F. Weng, J. Dai, Research and development status of laser cladding on magnesium alloys: A review, *Opt. Lasers Eng.* 93 (2017) 195–210. doi:10.1016/j.optlaseng.2017.02.007.
- [19] A. Farnia, F. Malek Ghaini, J. Sabbaghzadeh, Effects of pulse duration and

- overlapping factor on melting ratio in preplaced pulsed Nd:YAG laser cladding, *Opt. Lasers Eng.* 51 (2013) 69–76. doi:10.1016/j.optlaseng.2012.07.015.
- [20] G. Muvvala, D. Patra Karmakar, A.K. Nath, Online monitoring of thermocycles and its correlation with microstructure in laser cladding of nickel based super alloy, *Opt. Lasers Eng.* 88 (2017) 139–152. doi:10.1016/j.optlaseng.2016.08.005.
- [21] H. El Cheikh, B. Courant, S. Branchu, J.Y. Hascoët, R. Guillén, Analysis and prediction of single laser tracks geometrical characteristics in coaxial laser cladding process, *Opt. Lasers Eng.* 50 (2012) 413–422. doi:10.1016/j.optlaseng.2011.10.014.
- [22] O.G. Devojno, E. Feldshtein, M.A. Kardapolava, N.I. Lutsko, On the formation features, microstructure and microhardness of single laser tracks formed by laser cladding of a NiCrBSi self-fluxing alloy, *Opt. Lasers Eng.* 106 (2018) 32–38. doi:10.1016/j.optlaseng.2018.02.004.
- [23] J.T. Hofman, D.F. De Lange, B. Pathiraj, J. Meijer, FEM modeling and experimental verification for dilution control in laser cladding, *J. Mater. Process. Technol.* 211 (2011) 187–196. doi:10.1016/j.jmatprotec.2010.09.007.
- [24] C.-F. Hung, J. Lin, Solidification model of laser cladding with wire feeding technique, *J. Laser Appl.* 16 (2004) 140. doi:10.2351/1.1771167.
- [25] J. Do Kim, Y. Peng, Plunging method for Nd:YAG laser cladding with wire feeding, *Opt. Lasers Eng.* 33 (2000) 299–309. doi:10.1016/S0143-8166(00)00046-4.
- [26] K. Partes, Analytical model of the catchment efficiency in high speed laser cladding, *Surf. Coatings Technol.* 204 (2009) 366–371. doi:10.1016/j.surfcoat.2009.07.041.
- [27] J. Ibarra-Medina, A.J. Pinkerton, A CFD model of the laser, coaxial powder stream and substrate interaction in laser cladding, *Phys. Procedia.* 5 (2010) 337–346. doi:10.1016/j.phpro.2010.08.060.

- [28] Z. Zhang, P. Farahmand, R. Kovacevic, Laser cladding of 420 stainless steel with molybdenum on mild steel A36 by a high power direct diode laser, *Mater. Des.* 109 (2016) 686–699. doi:10.1016/j.matdes.2016.07.114.
- [29] Y. Huang, M.B. Khamesee, E. Toyserkani, A comprehensive analytical model for laser powder-fed additive manufacturing, *Addit. Manuf.* 12 (2016) 90–99. doi:10.1016/j.addma.2016.07.001.
- [30] S. Zekovic, R. Dwivedi, R. Kovacevic, Numerical simulation and experimental investigation of gas-powder flow from radially symmetrical nozzles in laser-based direct metal deposition, *Int. J. Mach. Tools Manuf.* 47 (2007) 112–123. doi:10.1016/j.ijmachtools.2006.02.004.
- [31] J. Lin, Numerical simulation of the focused powder streams in coaxial laser cladding, *J. Mater. Process. Technol.* 105 (2000) 17–23. doi:10.1016/S0924-0136(00)00584-7.
- [32] S.Y. Wen, Y.C. Shin, J.Y. Murthy, P.E. Sojka, Modeling of coaxial powder flow for the laser direct deposition process, *Int. J. Heat Mass Transf.* 52 (2009) 5867–5877. doi:10.1016/j.ijheatmasstransfer.2009.07.018.
- [33] G. Zhu, D. Li, A. Zhang, Y. Tang, Numerical simulation of metallic powder flow in a coaxial nozzle in laser direct metal deposition, *Opt. Laser Technol.* 43 (2011) 106–113. doi:10.1016/j.optlastec.2010.05.012.
- [34] I. Kovaleva, O. Kovalev, A. Zaitsev, I. Smurov, Numerical simulation and comparison of powder jet profiles for different types of coaxial nozzles in direct material deposition, *Phys. Procedia.* 41 (2013) 870–872. doi:10.1016/j.phpro.2013.03.160.
- [35] I. Smurov, M. Doubenskaia, A. Zaitsev, Comprehensive analysis of laser cladding by means of optical diagnostics and numerical simulation, *Surf. Coatings Technol.* 220 (2013) 112–121. doi:10.1016/j.surfcoat.2012.10.053.
- [36] J. Ibarra-Medina, M. Vogel, A.J. Pinkerton, A CFD model of laser cladding: From deposition head to melt pool dynamics, *Proc. 30th Int. Congr. Appl. Lasers Electro-Optics.* (2011) 378–386. <http://eprints.lancs.ac.uk/59716/>.
- [37] W. Devesse, D. De Baere, P. Guillaume, V.U. Brussel, Modeling of Laser

- Beam and Powder Flow Interaction in Laser Cladding Using Ray-Tracing, *J. Laser Appl.* 27 (2015) 0–8. doi:10.2351/1.4906394.
- [38] I. Tabernero, A. Lamikiz, S. Martínez, E. Ukar, L.N. López De Lacalle, Geometric modelling of added layers by coaxial Laser Cladding, *Phys. Procedia*. 39 (2012) 913–920. doi:10.1016/j.phpro.2012.10.116.
- [39] C.Y. Liu, J. Lin, Thermal processes of a powder particle in coaxial laser cladding, *Opt. Laser Technol.* 35 (2003) 81–86. doi:10.1016/S0030-3992(02)00145-7.
- [40] O.B. Kovalev, I.O. Kovaleva, I.Y. Smurov, Numerical investigation of gas-disperse jet flows created by coaxial nozzles during the laser direct material deposition, *J. Mater. Process. Technol.* 249 (2017) 118–127. doi:10.1016/j.jmatprotec.2017.05.041.
- [41] I. Tabernero, A. Lamikiz, E. Ukar, L.N. Lopez De Lacalle, C. Angulo, G. Urbikain, Numerical simulation and experimental validation of powder flux distribution in coaxial laser cladding, *J. Mater. Process. Technol.* 210 (2010) 2125–2134. doi:10.1016/j.jmatprotec.2010.07.036.
- [42] S. Wen, Y.C. Shin, Modeling of transport phenomena during the coaxial laser direct deposition process, *J. Appl. Phys.* 108 (2010) 1–9. doi:10.1063/1.3474655.
- [43] J. Lin, Laser attenuation of the focused powder streams in coaxial laser cladding, *J. Laser Appl.* 12 (2000). doi:10.2351/1.521910.
- [44] N. Yang, Concentration model based on movement model of powder flow in coaxial laser cladding, *Opt. Laser Technol.* 41 (2009) 94–98. doi:10.1016/j.optlastec.2008.03.008.
- [45] H. Pan, F. Liou, Numerical simulation of metallic powder flow in a coaxial nozzle for the laser aided deposition process, *Opt. Laser Technol.* 43 (2011) 106–113. doi:10.1016/j.jmatprotec.2004.11.017.
- [46] B. Zhang, C. Coddet, Numerical study on the effect of pressure and nozzle dimension on particle distribution and velocity in laser cladding under vacuum base on CFD, *J. Manuf. Process.* 23 (2016) 54–60.

doi:10.1016/j.jmapro.2016.05.019.

- [47] I. Tabernero, A. Lamikiz, S. Martínez, E. Ukar, L.N. López De Lacalle, Modelling of energy attenuation due to powder flow-laser beam interaction during laser cladding process, *J. Mater. Process. Technol.* 212 (2012) 516–522. doi:10.1016/j.jmatprotec.2011.10.019.
- [48] J. Liu, L. Li, Y. Zhang, X. Xie, Attenuation of laser power of a focused Gaussian beam during interaction between a laser and powder in coaxial laser cladding, *J. Phys. D. Appl. Phys.* 38 (2005) 1546–1550. doi:10.1088/0022-3727/38/10/008.
- [49] I.O. Kovaleva, O.B. Kovalev, Simulation of light-propulsion acceleration of powder particles for laser direct metal deposition, *Phys. Procedia.* 12 (2011) 285–295. doi:10.1016/j.phpro.2011.03.037.
- [50] I.O. Kovaleva, O.B. Kovalev, Simulation of the acceleration mechanism by light-propulsion for the powder particles at laser direct material deposition, *Opt. Laser Technol.* 44 (2012) 714–725. doi:10.1016/j.optlastec.2011.09.016.
- [51] J. Ibarra-Medina, a. J. Pinkerton, A numerical investigation of powder heating in coaxial laser direct metal deposition, 36th MATADOR Conf. 27 (2010) 1–4. doi:10.1007/978-1-84996-432-6_101.
- [52] O.O. Diniz Neto, a. M. Alcalde, R. Vilar, Interaction of a focused laser beam and a coaxial powder jet in laser surface processing, *J. Laser Appl.* 19 (2007) 84. doi:10.2351/1.2402523.
- [53] S. Wen, Y.C. Shin, Modeling of the Off-Axis High Power Diode Laser Cladding Process, *J. Heat Transfer.* 133 (2011) 31007. doi:10.1115/1.4002447.
- [54] P. Nie, O.A. Ojo, Z. Li, Modeling analysis of laser cladding of a nickel-based superalloy, *Surf. Coatings Technol.* 258 (2014) 1048–1059. doi:10.1016/j.surfcoat.2014.07.030.
- [55] P. Balu, P. Leggett, R. Kovacevic, Parametric study on a coaxial multi-material powder flow in laser-based powder deposition process, *J. Mater. Process. Technol.* 212 (2012) 1598–1610. doi:10.1016/j.jmatprotec.2012.02.020.
- [56] Y. Lee, D.F. Farson, Simulation of transport phenomena and melt pool shape

- for multiple layer additive manufacturing, *J. Laser Appl.* 28 (2016) 12006. doi:10.2351/1.4935711.
- [57] Y. Cao, J. Choi, Solidification Microstructure Evolution Model for Laser Cladding Process, *J. Heat Transfer.* 129 (2007) 852. doi:10.1115/1.2712856.
 - [58] H. Qi, J. Mazumder, H. Ki, Numerical simulation of heat transfer and fluid flow in coaxial laser cladding process for direct metal deposition, *J. Appl. Phys.* 100 (2006) 1–11. doi:10.1063/1.2209807.
 - [59] M. Picasso, A.F.A. Hoadley, Finite element simulation of Laser Surface Treatments including convection in the melt pool, 4 (1994) 61–83.
 - [60] Y. Lee, M. Nordin, S. Babu, D. Farson, Influence of Fluid Convection on Weld Pool Formation in Laser Cladding, *Weld. J.* 93 (2014) 292s–300s.
 - [61] J. Do Kim, Y. Peng, Melt pool shape and dilution of laser cladding with wire feeding, *J. Mater. Process. Technol.* 104 (2000) 284–293. doi:10.1016/S0924-0136(00)00528-8.
 - [62] W. Ya, B. Pathiraj, S. Liu, 2D modelling of clad geometry and resulting thermal cycles during laser cladding, *J. Mater. Process. Technol.* 230 (2016) 217–232. doi:10.1016/j.jmatprotec.2015.11.012.
 - [63] L. Han, K.M. Phatak, F.W. Liou, Modeling of laser cladding with powder injection, *Metall. Mater. Trans. B.* 35 (2004) 1139–1150. doi:10.1007/s11663-004-0070-0.
 - [64] J. Choi, L. Han, Y. Hua, Modeling and Experiments of Laser Cladding With Droplet Injection, *J. Heat Transfer.* 127 (2005) 978. doi:10.1115/1.2005273.
 - [65] C. Chan, J. Mazumder, M.M. Chen, A two-dimensional transient model for convection in laser melted pool, *Metall. Trans. A.* 15 (1984) 2175–2184. doi:10.1007/BF02647100.
 - [66] F. Kong, R. Kovacevic, Modeling of heat transfer and fluid flow in the laser multilayered cladding process, *Metall. Mater. Trans. B Process Metall. Mater. Process. Sci.* 41 (2010) 1310–1320. doi:10.1007/s11663-010-9412-2.
 - [67] F.K. Mirzade, V.G. Niziev, V.Y. Panchenko, M.D. Khomenko, R. V. Grishaev,

- S. Pityana, C. Van Rooyen, Kinetic approach in numerical modeling of melting and crystallization at laser cladding with powder injection, *Phys. B Condens. Matter.* 423 (2013) 69–76. doi:10.1016/j.physb.2013.04.053.
- [68] J. Esmaeelpanah, M. Passandideh-Fard, On a Numerical Model of Laser Cladding Process, in: *Proc. 14th Int. Heat Transf. Conf. IHTC14*, Washington, DC, USA, 2010: pp. 1–8.
- [69] S. Morville, M. Carin, 2D longitudinal modeling of heat transfer and fluid flow during multilayered direct laser metal deposition process, *J. Laser Appl.* 24 (2012) 1–4. doi:10.2351/1.4726445.
- [70] A. Kumar, S. Roy, Effect of three-dimensional melt pool convection on process characteristics during laser cladding, *Comput. Mater. Sci.* 46 (2009) 495–506. doi:10.1016/j.commatsci.2009.04.002.
- [71] M. Hao, Y. Sun, A FEM model for simulating temperature field in coaxial laser cladding of Ti6AL4V alloy using an inverse modeling approach, *Int. J. Heat Mass Transf.* 64 (2013) 352–360. doi:10.1016/j.ijheatmasstransfer.2013.04.050.
- [72] L.F. Guo, T.M. Yue, H.C. Man, A finite element method approach for thermal analysis of laser cladding of magnesium alloy with preplaced Al–Si powder, *J. Laser Appl.* 16 (2004) 229. doi:10.2351/1.1809634.
- [73] Y. Lei, R. Sun, Y. Tang, W. Niu, Numerical simulation of temperature distribution and TiC growth kinetics for high power laser clad TiC/NiCrBSiC composite coatings, *Opt. Laser Technol.* 44 (2012) 1141–1147. doi:10.1016/j.optlastec.2011.09.030.
- [74] V. Yevko, C.B. Park, G. Zak, T.W. Coyle, B. Benhabib, Cladding formation in laser-beam fusion of metal powder, *Universi of Toronto*, 1998. doi:10.1108/13552549810239021.
- [75] M.F. Gouge, J.C. Heigel, P. Michaleris, T.A. Palmer, Modeling forced convection in the thermal simulation of laser cladding processes, *Int. J. Adv. Manuf. Technol.* (2015) 307–320. doi:10.1007/s00170-015-6831-x.
- [76] F. Luo, J. Yao, X. Hu, G. Chai, Effect of Laser Power on the Cladding

- Temperature Field and the Heat Affected Zone, *J. Iron Steel Res. Int.* 18 (2011) 73–78. doi:10.1016/S1006-706X(11)60014-9.
- [77] A.F.A. Hoadley, M. Rappaz, A Thermal Model of Laser Cladding by Powder Injection, *Metall. Trans. B.* 23B (1992) 631–642.
- [78] E. Toyserkani, A. Khajepour, S. Corbin, 3-D finite element modeling of laser cladding by powder injection: Effects of laser pulse shaping on the process, *Opt. Lasers Eng.* 41 (2004) 849–867. doi:10.1016/S0143-8166(03)00063-0.
- [79] Y.L. Huang, J. Liu, N.H. Ma, J.-G. Li, Three-dimensional analytical model on laser-powder interaction during laser cladding, *J. Laser Appl.* 18 (2006) 42. doi:10.2351/1.2164476.
- [80] M. Alimardani, E. Toyserkani, J.P. Huissoon, A 3D dynamic numerical approach for temperature and thermal stress distributions in multilayer laser solid freeform fabrication process, *Opt. Lasers Eng.* 45 (2007) 1115–1130. doi:10.1016/j.optlaseng.2007.06.010.
- [81] H. El Cheikh, B. Courant, 3D Finite Element Simulation to Predict the Induced Thermal Field in Case of Laser Cladding Process and Half Cylinder Laser Clad, 1 (2012) 55–59.
- [82] Y. Lei, R. Sun, J. Lei, Y. Tang, W. Niu, A new theoretical model for high power laser clad TiC/NiCrBSiC composite coatings on Ti6Al4V alloys, *Opt. Lasers Eng.* 48 (2010) 899–905. doi:10.1016/j.optlaseng.2010.03.016.
- [83] A.F.H. Kaplan, G. Groboth, Process Analysis of Laser Beam Cladding, *J. Manuf. Sci. Eng.* 123 (2001) 609. doi:10.1115/1.1344899.
- [84] W.C. Tseng, J.N. Aoh, Simulation study on laser cladding on preplaced powder layer with a tailored laser heat source, *Opt. Laser Technol.* 48 (2013) 141–152. doi:10.1016/j.optlastec.2012.09.014.
- [85] Y. Yong, W. Fu, Q. Deng, D. Chen, A comparative study of vision detection and numerical simulation for laser cladding of nickel-based alloy, *J. Manuf. Process.* 28 (2017) 364–372. doi:10.1016/j.jmapro.2017.03.004.
- [86] R. Parekh, R.K. Buddu, R.I. Patel, Multiphysics simulation of laser cladding process to study the effect of process parameters on clad geometry, *Procedia*

- Technol. 23 (2016) 529–536. doi:10.1016/j.protcy.2016.03.059.
- [87] P. Farahmand, R. Kovacevic, Laser cladding assisted with an induction heater (LCAIH) of Ni-60%WC coating, J. Mater. Process. Technol. 222 (2015) 244–258. doi:10.1016/j.jmatprotec.2015.02.026.
 - [88] P. Farahmand, R. Kovacevic, An experimental–numerical investigation of heat distribution and stress field in single- and multi-track laser cladding by a high-power direct diode laser, Opt. Laser Technol. 63 (2014) 154–168. doi:10.1016/j.optlastec.2014.04.016.
 - [89] X. He, G. Yu, J. Mazumder, Temperature and composition profile during double-track laser cladding of H13 tool steel, J. Phys. D. Appl. Phys. 43 (2010). doi:10.1088/0022-3727/43/1/015502.
 - [90] H. Liu, X. Qin, S. Huang, Z. Hu, M. Ni, Geometry modeling of single track cladding deposited by high power diode laser with rectangular beam spot, Opt. Lasers Eng. 100 (2018) 38–46. doi:10.1016/j.optlaseng.2017.07.008.
 - [91] D. V. Bedenko, O.B. Kovalev, I. Smurov, A. V. Zaitsev, Numerical simulation of transport phenomena, formation the bead and thermal behavior in application to industrial DMD technology, Int. J. Heat Mass Transf. 95 (2016) 902–912. doi:10.1016/j.ijheatmasstransfer.2015.12.046.
 - [92] J. Lin, W.M. Steen, An in-process method for the inverse estimation of the powder catchment efficiency during laser cladding, Opt. Laser Technol. 30 (1998) 77–84. doi:10.1016/S0030-3992(98)00007-3.
 - [93] M. Zeinali, A. Khajepour, Development of an adaptive fuzzy logic-based inverse dynamic model for laser cladding process, Eng. Appl. Artif. Intell. 23 (2010) 1408–1419. doi:10.1016/j.engappai.2009.11.006.
 - [94] T. Chande, J. Mazumder, Two-Dimensional, Transient Model for Mass-Transport in Laser Surface Alloying, J. Appl. Phys. 57 (1985) 2226–2232. doi:10.1063/1.334367.
 - [95] G. Palumbo, S. Pinto, L. Tricarico, Numerical finite element investigation on laser cladding treatment of ring geometries, J. Mater. Process. Technol. 155–156 (2004) 1443–1450. doi:10.1016/j.jmatprotec.2004.04.360.

- [96] R. Raju, V. Petley, A. G. K., M. Duraiselvam, S. Verma, R. Rajendran, Numerical finite element investigation on Laser Cladding of aerospace components, *Life Cycle Reliab. Saf. Eng.* 3 (2014) 13–23.
- [97] Y.S. Lee, W. Zhang, Modeling of heat transfer, fluid flow and solidification microstructure of nickel-base superalloy fabricated by laser powder bed fusion, *Addit. Manuf.* 12 (2016) 178–188. doi:10.1016/j.addma.2016.05.003.
- [98] M. Masoomi, S.M. Thompson, N. Shamsaei, Laser powder bed fusion of Ti-6Al-4V parts: Thermal modeling and mechanical implications, *Int. J. Mach. Tools Manuf.* 118–119 (2017) 73–90. doi:10.1016/j.ijmachtools.2017.04.007.
- [99] N. Nazemi, R.J. Urbanic, A numerical investigation for alternative toolpath deposition solutions for surface cladding of stainless steel P420 powder on AISI 1018 steel substrate, *Int. J. Adv. Manuf. Technol.* 96 (2018) 4123–4143. doi:10.1007/s00170-018-1840-1.
- [100] L. Song, V. Bagavath-Singh, B. Dutta, J. Mazumder, Control of melt pool temperature and deposition height during direct metal deposition process, *Int. J. Adv. Manuf. Technol.* 58 (2012) 247–256. doi:10.1007/s00170-011-3395-2.
- [101] H. Kohler, C. Thomy, F. Vollertsen, Contact-less temperature measurement and control with applications to laser cladding, *Weld. World.* 60 (2016) 1–9. doi:10.1007/s40194-015-0275-7.
- [102] H.S. Tran, J.T. Tchuindjang, H. Paydas, A. Mertens, R.T. Jardin, L. Duchêne, R. Carrus, J. Lecomte-Beckers, A.M. Habraken, 3D thermal finite element analysis of laser cladding processed Ti6Al4V part with microstructural correlations, *Mater. Des.* 128 (2017) 130–142. doi:10.1016/j.matdes.2017.04.092.
- [103] A. Suarez, M.J. Tobar, A. Yaez, I. Perez, J. Sampedro, V. Amigo, J.J. Candel, Modeling of phase transformations of Ti6Al4V during laser metal deposition, *Phys. Procedia.* 12 (2011) 666–673. doi:10.1016/j.phpro.2011.03.083.
- [104] P. Kongsuwan, G. Brandal, Y. Lawrence Yao, Laser Induced Porosity and Crystallinity Modification of a Bioactive Glass Coating on Titanium Substrates,

- J. Manuf. Sci. Eng. 137 (2015) 31004. doi:10.1115/1.4029566.
- [105] Y. Lee, M. Nordin, S.S. Babu, D.F. Farson, Effect of fluid convection on dendrite arm spacing in laser deposition, *Metall. Mater. Trans. B Process Metall. Mater. Process. Sci.* 45 (2014) 1520–1529. doi:10.1007/s11663-014-0054-7.
- [106] W. Gao, S. Zhao, Y. Wang, Z. Zhang, F. Liu, X. Lin, Numerical simulation of thermal field and Fe-based coating doped Ti, *Int. J. Heat Mass Transf.* 92 (2016) 83–90. doi:10.1016/j.ijheatmasstransfer.2015.08.082.
- [107] P. Farahmand, P. Balu, F. Kong, R. Kovacevic, Investigation of Thermal Cycle and Hardness Distribution in the Laser Cladding of AISI H13 tool steel produced by a High Power Direct Diode Laser, in: *Proc. ASME 2013 Int. Mech. Eng. Congr. Expo.*, Callifornia, USA, 2015: pp. 1–12.
- [108] S. Santhanakrishnan, F. Kong, R. Kovacevic, An experimentally based thermo-kinetic hardening model for high power direct diode laser cladding, *J. Mater. Process. Technol.* 211 (2011) 1247–1259. doi:10.1016/j.jmatprotec.2011.02.006.
- [109] S. Gu, G. Chai, H. Wu, Y. Bao, Characterization of local mechanical properties of laser-cladding H13-TiC composite coatings using nanoindentation and finite element analysis, *Mater. Des.* 39 (2012) 72–80. doi:10.1016/j.matdes.2012.02.028.
- [110] A. Suarez, J.M. Amado, M.J. Tobar, A. Yanez, E. Fraga, M.J. Peel, Study of residual stresses generated inside laser clad plates using FEM and diffraction of synchrotron radiation, *Surf. Coatings Technol.* 204 (2010) 1983–1988. doi:10.1016/j.surfcoat.2009.11.037.
- [111] A. Deus, M., J. Mazumder, Three-dimensional finite element models for the calculation of temperature and residual stress fields in laser cladding, *Arbor.* 1001 (2006) 48109.
- [112] R.J. Moat, A.J. Pinkerton, L. Li, P.J. Withers, M. Preuss, Residual stresses in laser direct metal deposited Waspaloy, *Mater. Sci. Eng. A.* 528 (2011) 2288–2298. doi:10.1016/j.msea.2010.12.010.

- [113] A. Plati, J.C. Tan, I.O. Golosnoy, R. Persoons, K. Van Acker, T.W. Clyne, Residual stress generation during laser cladding of steel with a particulate metal matrix composite, *Adv. Eng. Mater.* 8 (2006) 619–624. doi:10.1002/adem.200600063.
- [114] S. Paul, K. Ashraf, R. Singh, Residual stress modeling of powder injection laser surface cladding for die repair applications, *ASME 2014 Int. Manuf. Sci. Eng. Conf. MSEC 2014 Collocated with JSME 2014 Int. Conf. Mater. Process. 42nd North Am. Manuf. Res. Conf.* 2 (2014) 1–8. doi:10.1115/MSEC2014-4029.
- [115] N.S. Bailey, C. Katinas, Y.C. Shin, Laser direct deposition of AISI H13 tool steel powder with numerical modeling of solid phase transformation, hardness, and residual stresses, *J. Mater. Process. Technol.* 247 (2017) 223–233. doi:10.1016/j.jmatprotec.2017.04.020.
- [116] M.M. Alam, A.F.H. Kaplan, J. Tuominen, P. Vuoristo, J. Miettinen, J. Poutala, J. Näkki, J. Junkala, T. Peltola, Z. Barsoum, Analysis of the stress raising action of flaws in laser clad deposits, *Mater. Des.* 46 (2013) 328–337. doi:10.1016/j.matdes.2012.10.010.
- [117] S. Paul, K. Thool, R. Singh, I. Samajdar, W. Yan, Experimental Characterization of Clad Microstructure and its Correlation with Residual Stresses, *Procedia Manuf.* 0 (2017) 804–818. doi:10.1016/j.promfg.2017.07.081.
- [118] W. Jiang, Z. Liu, J.M. Gong, S.T. Tu, Numerical simulation to study the effect of repair width on residual stresses of a stainless steel clad plate, *Int. J. Press. Vessel. Pip.* 87 (2010) 457–463. doi:10.1016/j.ijpvp.2010.06.003.
- [119] F. Brückner, D. Lepski, E. Beyer, Modeling the Influence of Process Parameters and Additional Heat Sources on Residual Stresses in Laser Cladding, *J. Therm. Spray Technol.* 16 (2007) 355–373. doi:10.1007/s11666-007-9026-7.
- [120] M. Krzyzanowski, S. Bajda, Y. Liu, A. Triantaphyllou, W.M. Rainforth, M. Glendenning, M. Krzyzanowski, S. Bajda, Y. Liu, 3D analysis of thermal and stress evolution during laser cladding of bioactive glass coatings, *J. Mech.*

Behav. Biomed. Mater. 59 (2016) 404–417.
doi:10.1016/j.jmbbm.2016.02.023.

- [121] Y. Chew, J.H.L. Pang, Fatigue life prediction model for laser clad AISI 4340 specimens with multiple surface cracks, *Int. J. Fatigue*. 87 (2016) 235–244. doi:10.1016/j.ijfatigue.2016.01.025.
- [122] S. Paul, I. Gupta, R.K. Singh, Characterization and Modeling of Microscale Preplaced Powder Cladding Via Fiber Laser, *J. Manuf. Sci. Eng.* 137 (2015) 31019. doi:10.1115/1.4029922.
- [123] M. Dhanda, B. Halder, P. Saha, Development and Characterization of Hard and Wear Resistant MMC Coating on Ti-6Al-4V Substrate by Laser Cladding, *Procedia Mater. Sci.* 6 (2014) 1226–1232. doi:10.1016/j.mspro.2014.07.196.
- [124] H.C. Li, D.G. Wang, C.Z. Chen, F. Weng, Effect of CeO₂ and Y₂O₃ on microstructure, bioactivity and degradability of laser cladding CaO-SiO₂ coating on titanium alloy, *Colloids Surfaces B Biointerfaces*. 127 (2015) 15–21. doi:10.1016/j.colsurfb.2015.01.016.
- [125] M.R. Fernández, A. García, J.M. Cuetos, R. González, A. Noriega, M. Cadenas, Effect of actual WC content on the reciprocating wear of a laser cladding NiCrBSi alloy reinforced with WC, *Wear*. 324–325 (2015) 80–89. doi:10.1016/j.wear.2014.12.021.
- [126] S. Da Sun, Q. Liu, M. Brandt, V. Luzin, R. Cottam, M. Janardhana, G. Clark, Effect of laser clad repair on the fatigue behaviour of ultra-high strength AISI 4340 steel, *Mater. Sci. Eng. A*. 606 (2014) 46–57. doi:10.1016/j.msea.2014.03.077.
- [127] J.N. Li, S.L. Gong, M. Sun, F.H. Shan, X.C. Wang, S. Jiang, Effect of Sb on physical properties and microstructures of laser nano/amorphous-composite film, *Phys. B Condens. Matter*. 428 (2013) 73–77. doi:10.1016/j.physb.2013.07.018.
- [128] J.L. Chen, J. Li, R. Song, L.L. Bai, J.Z. Shao, C.C. Qu, Effect of the scanning speed on microstructural evolution and wear behaviors of laser cladding NiCrBSi composite coatings, *Opt. Laser Technol.* 72 (2015) 86–99.

doi:10.1016/j.optlastec.2015.03.015.

- [129] X.B. Liu, H.Q. Liu, X.J. Meng, C.F. Sun, M. Di Wang, L.H. Qi, G.L. Shi, S.H. Wu, Effects of aging treatment on microstructure and tribological properties of nickel-based high-temperature self-lubrication wear resistant composite coatings by laser cladding, *Mater. Chem. Phys.* 143 (2014) 616–621. doi:10.1016/j.matchemphys.2013.09.043.
- [130] P. Kattire, S. Paul, R. Singh, W. Yan, Experimental characterization of laser cladding of CPM 9V on H13 tool steel for die repair applications, *J. Manuf. Process.* 20 (2015) 492–499. doi:10.1016/j.jmapro.2015.06.018.
- [131] W.H. Jiang, R. Kovacevic, Laser deposited TiC/H13 tool steel composite coatings and their erosion resistance, *J. Mater. Process. Technol.* 186 (2007) 331–338. doi:10.1016/j.jmatprotec.2006.12.053.
- [132] W. Jiang, P. Molian, Nanocrystalline TiC powder alloying and glazing of H13 steel using a CO₂ laser for improved life of die-casting dies, *Surf. Coatings Technol.* 135 (2001) 139–149. doi:10.1016/S0257-8972(00)01075-6.
- [133] J.C. Pereira, J.C. Zambrano, M.J. Tobar, A. Yanez, V. Amig, High temperature oxidation behavior of laser cladding MCrAlY coatings on austenitic stainless steel, *Surf. Coatings Technol.* 270 (2015) 243–248. doi:10.1016/j.surfcoat.2015.02.050.
- [134] B. Abiodun, A. Andrews, M.T. Mathew, P. Apata, S. Pityana, Applied Surface Science Improving the tribocorrosion resistance of Ti6Al4V surface by laser surface cladding with TiNiZrO₂ composite coating, *Appl. Surf. Sci.* 345 (2015) 99–108. doi:10.1016/j.apsusc.2015.03.152.
- [135] J. Li, H. Yu, S. Gong, C. Chen, F. Weng, L. Ding, Y. Pan, F. Shan, Influence of Al₂O₃-Y₂O₃ and Ce-Al-Ni amorphous alloy on physical properties of laser synthetic composite coatings on titanium alloys, *Surf. Coatings Technol.* 247 (2014) 55–60. doi:10.1016/j.surfcoat.2014.03.007.
- [136] M. Doubenskaia, A.K. Gilmudinov, K.Y. Nagulin, Surface & Coatings Technology Laser cladding of metal matrix composites reinforced by cermet inclusions for dry friction applications at ambient and elevated temperatures,

Surf. Coat. Technol. 276 (2015) 696–703.
doi:10.1016/j.surfcoat.2015.05.044.

- [137] B. Cárcel, A. Serrano, J. Zambrano, V. Amigó, A.C. Cárcel, Laser cladding of TiAl intermetallic alloy on Ti6Al4V. Process optimization and properties, *Phys. Procedia*. 56 (2014) 284–293. doi:10.1016/j.phpro.2014.08.173.
- [138] J.N. Li, S.L. Gong, H. Liu, H.X. Li, Physical properties and microstructures of Fe₃Al matrix laser amorphous-nanocrystals reinforced coating, *Mater. Lett.* 92 (2013) 235–238. doi:10.1016/j.matlet.2012.10.085.
- [139] D.I. Adebisi, A.P.I. Popoola, Mitigation of abrasive wear damage of Ti6Al4V by laser surface alloying, *Mater. Des.* 74 (2015) 67–75. doi:10.1016/j.matdes.2015.02.010.
- [140] F. Weng, H. Yu, C. Chen, J. Liu, L. Zhao, Microstructures and properties of TiN reinforced Co-based composite coatings modified with Y₂O₃ by laser cladding on Ti–6Al–4V alloy, *J. Alloys Compd.* 650 (2015) 178–184. doi:10.1016/j.jallcom.2015.07.295.
- [141] J.N. Li, S.L. Gong, Y.N. Shi, H.B. Suo, X.C. Wang, Y.H. Deng, F.H. Shan, J.Q. Li, Microstructure and physical properties of laser Zn modified amorphous-nanocrystalline coating on a titanium alloy, *Phys. E Low-Dimensional Syst. Nanostructures*. 56 (2014) 296–300. doi:10.1016/j.physe.2013.09.017.
- [142] Y. Lin, Y. Lei, H. Fu, J. Lin, Mechanical properties and toughening mechanism of TiB₂/NiTi reinforced titanium matrix composite coating by laser cladding, *Mater. Des.* 80 (2015) 82–88. doi:10.1016/j.matdes.2015.05.009.
- [143] X.H. Wang, A.M. Liu, Microstructure and abrasive-wear behavior under high temperature of laser Clad Ni-based WC ceramic coating, *Phys. Procedia*. 50 (2013) 145–149. doi:10.1016/j.phpro.2013.11.024.
- [144] J. Lambarri, J. Leunda, V. García Navas, C. Soriano, C. Sanz, Microstructural and tensile characterization of Inconel 718 laser coatings for aeronautic components, *Opt. Lasers Eng.* 51 (2013) 813–821. doi:10.1016/j.optlaseng.2013.01.011.
- [145] A. Mthisi, A.P.I. Popoola, D.I. Adebisi, O.M. Popoola, Laser Cladding of Ti-

- 6Al-4V Alloy with Ti-Al₂O₃ Coating for Biomedical Applications, IOP Conf. Ser. Mater. Sci. Eng. 350 (2018). doi:10.1088/1757-899X/350/1/012005.
- [146] R.L. Sun, Y.W. Lei, W. Niu, Laser clad TiC reinforced NiCrBSi composite coatings on Ti-6Al-4V alloy using a CW CO₂ laser, Surf. Coatings Technol. 203 (2009) 1395–1399. doi:10.1016/j.surfcoat.2008.11.012.
- [147] M. Lu, P. McCormick, Y. Zhao, Z. Fan, H. Huang, Laser deposition of compositionally graded titanium oxide on Ti6Al4V alloy, Ceram. Int. 44 (2018) 20851–20861. doi:10.1016/j.ceramint.2018.08.090.
- [148] Additive Manufacturing, Loughborough University, (2018). <https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/> (accessed April 26, 2019).
- [149] 3D HUBS, (2018). <https://www.3dhubs.com/knowledge-base/additive-manufacturing-technologies-overview> (accessed April 26, 2019).
- [150] W. Du, IMECE2017-70344 Binder Jetting Additive Manufacturing of Ceramics : A Literature, (2018) 1–12.
- [151] J. Gonzalez-Gutierrez, S. Cano, S. Schuschnigg, C. Kukla, J. Sapkota, C. Holzer, Additive Manufacturing of Metallic and Ceramic Components by the Material Extrusion of Highly-filled Polymers A Review and Future Perspectives, (2018). doi:10.3390/ma11050840.
- [152] J. Dilag, T. Chen, S. Li, S.A. Bateman, Design and direct additive manufacturing of three-dimensional surface micro-structures using material jetting technologies, Addit. Manuf. 27 (2019) 167–174. doi:10.1016/j.addma.2019.01.009.
- [153] T. Hafkamp, G. Van Baars, B. De Jager, P. Etman, A feasibility study on process monitoring and control in vat photopolymerization of ceramics, Mechatronics. 56 (2018) 220–241. doi:10.1016/j.mechatronics.2018.02.006.
- [154] P.M. Bhatt, A.M. Kabir, M. Peralta, H.A. Bruck, S.K. Gupta, A robotic cell for performing sheet lamination-based additive manufacturing, Addit. Manuf. 27 (2019) 278–289. doi:10.1016/j.addma.2019.02.002.
- [155] A. Haridas, M. Vadakke, A. Crivoi, P. Patinharekandy, T. Ming, K. Chan,

- Surface roughness evaluation of additive manufactured metallic components from white light images captured using a flexible fiberscope, *Opt. Lasers Eng.* 110 (2018) 262–271. doi:10.1016/j.optlaseng.2018.05.026.
- [156] S. Donadello, M. Motta, A.G. Demir, B. Previtali, Monitoring of laser metal deposition height by means of coaxial laser triangulation, 112 (2019) 136–144. doi:10.1016/j.optlaseng.2018.09.012.
- [157] C. Ni, Y. Shi, J. Liu, G. Huang, Characterization of Al_{0.5}FeCu_{0.7}NiCoCr high-entropy alloy coating on aluminum alloy by laser cladding, *Opt. Laser Technol.* 105 (2018) 257–263. doi:10.1016/j.optlastec.2018.01.058.
- [158] D. Jiang, C. Hong, M. Zhong, M. Alkhayat, A. Weisheit, A. Gasser, H. Zhang, I. Kelbassa, R. Poprawe, Fabrication of nano-TiCp reinforced Inconel 625 composite coatings by partial dissolution of micro-TiCp through laser cladding energy input control, *Surf. Coat. Technol.* 249 (2014) 125–131. doi:10.1016/j.surfcoat.2014.03.057.
- [159] J.M.S.P. Torres, T. Leonor, M. Morgado, H. Navas, Innovative Automation Equipment of Laser Cladding, (2015). doi:10.13140/RG.2.1.3675.4002.
- [160] Laser Cladding System Market Outlook, (2019). <https://businessherald.co/tag/laser-cladding-system-market-outlook/> (accessed April 26, 2019).
- [161] D. Wang, Q. Hu, Y. Zheng, Y. Xie, X. Zeng, Study on deposition rate and laser energy efficiency of Laser-Induction Hybrid Cladding, *Opt. Laser Technol.* 77 (2016) 16–22. doi:10.1016/j.optlastec.2015.08.019.
- [162] M. Li, B. Han, Y. Wang, L. Song, L. Guo, Investigation on laser cladding high-hardness nano-ceramic coating assisted by ultrasonic vibration processing, *Opt. - Int. J. Light Electron Opt.* 127 (2016) 4596–4600. doi:10.1016/j.ijleo.2016.01.194.
- [163] F.P. Incropera, T.L. Bergman, A.S. Lavine, D.P. DeWitt, Fundamentals of heat and mass transfer., 7th ed., Don Fowley, Jefferson, USA, 2011. doi:10.1017/CBO9781107415324.004.
- [164] D. Wang, Q. Hu, X. Zeng, Residual stress and cracking behaviors of

- Cr₁₃Ni₅Si₂ based composite coatings prepared by laser-induction hybrid cladding, *Surf. Coatings Technol.* 274 (2015) 51–59. doi:10.1016/j.surfcoat.2015.04.035.
- [165] S.H. Avner, *Introduction to Physical Metallurgy*, 1st ed., McGraw-Hill, Singapore, 1974.
- [166] P. Auerkari, *Mechanical and physical properties of engineering alumina ceramics*, 1996.
- [167] TiC,
http://www.matweb.com/search/datasheet_print.aspx?matguid=058d1b70edbd4b2293f298c52bbf9818. (2018).
- [168] Titanium Dioxide, AZOMaterial. (2002).
<https://www.azom.com/properties.aspx?ArticleID=1179> (accessed September 29, 2017).
- [169] AZoM, Zirconium Dioxide,
<https://www.azom.com/properties.aspx?ArticleID=133>, 31/10/2017,. (2002).
<https://www.azom.com/properties.aspx?ArticleID=133> (accessed October 31, 2017).
- [170] Titanium Alloys - Ti6Al4V, AZO Mater. (2000).
<https://www.azom.com/properties.aspx?ArticleID=1547> (accessed January 2, 2019).
- [171] SiC, AZOMaterial. (2000).
<https://www.azom.com/properties.aspx?ArticleID=42> (accessed January 2, 2019).
- [172] Titanium Nitride, MatWeb Mater. Prop. Data. (1996).
<http://www.matweb.com/search/datasheet.aspx?matguid=c4aa1b1bf8474216b4b593619d639e99&ckck=1> (accessed January 2, 2019).
- [173] I.R. Kabir, D. Yin, N. Tamanna, S. Naher, Thermomechanical modelling of laser surface glazing for H13 tool steel, *Appl. Phys. A Mater. Sci. Process.* 124 (2018) 0. doi:10.1007/s00339-018-1671-9.
- [174] Alumina AZOM, (2018). <https://www.azom.com/properties.aspx?ArticleID=52>

(accessed October 12, 2018).

- [175] X. Wang, T. Laoui, Lasers and materials in selective laser sintering, 23 (2006) 357–371.
- [176] H13 steel, matweb, (1996).
http://www.matweb.com/search/datasheet_print.aspx?matguid=e30d1d1038164808a85cf7ba6aa87ef7 (accessed July 8, 2019).
- [177] N. Tamanna, R. Crouch, I.R. Kabir, S. Naher, An analytical model to predict and minimize the residual stress of laser cladding process, Appl. Phys. A Mater. Sci. Process. 124 (2018) 0. doi:10.1007/s00339-018-1585-6.
- [178] E.R. Delinger, Thermo-mechanical model development and experimental validation for metallic parts in additive manufacturing, PhD, The Pennsylvania State University, 2015.
- [179] R. Cottam, M. Brandt, Laser cladding of Ti6Al4V powder on Ti6Al4V substrate: Effect of laser cladding parameters on microstructure, Phys. Procedia. 12 (2011) 323–329. doi:10.1016/j.phpro.2011.03.041.
- [180] J. Yang, H. Yu, J. Yin, M. Gao, Z. Wang, X. Zeng, Formation and control of martensite in Ti-6Al-4V alloy produced by selective laser melting, Mater. Des. 108 (2016) 308–318. doi:10.1016/j.matdes.2016.06.117.
- [181] B. Vrancken, L. Thijs, J.P. Kruth, J. Van Humbeeck, Heat treatment of Ti6Al4V produced by Selective Laser Melting: Microstructure and mechanical properties, J. Alloys Compd. 541 (2012) 177–185. doi:10.1016/j.jallcom.2012.07.022.
- [182] P. Barriobero-Vila, Effect of heat treatments on the microstructure of deformed Ti-6Al-4V, (2010) 69.
- [183] R. Cottam, Stress Relief Heat Treatment for Laser Cladding Repair of Ti-6Al-4V Aircraft Components Introduction, (2013).
- [184] D.F.D.J. Browne, K.T. Stanton, F.R. Chang-di, A review of the processing , composition , and temperature-dependent mechanical and thermal properties of dielectric technical ceramics, (2012) 4211–4235. doi:10.1007/s10853-011-6140-1.

- [185] Titanium carbide, MEMSnet. (2017). <https://www.memsnet.org/material/titaniumcarbidebulk/> (accessed January 3, 2019).
- [186] Z. Fan, M. Lu, H. Huang, Selective laser melting of alumina: A single track study, *Ceram. Int.* 44 (2018) 9484–9493. doi:10.1016/j.ceramint.2018.02.166.
- [187] S. Liu, Y.C. Shin, Simulation and experimental studies on microstructure evolution of resolidified dendritic TiCx in laser direct deposited Ti-TiC composite, *Mater. Des.* 159 (2018) 212–223. doi:10.1016/j.matdes.2018.08.053.
- [188] X.K. Zhu, Y.J. Chao, Effects of temperature-dependent material properties on welding simulation, 80 (2002) 967–976.
- [189] Y. Zhang, Y. Yi, S. Huang, H. He, Influence of Temperature-Dependent Properties of Aluminum Alloy on Evolution of Plastic Strain and, (2017). doi:10.3390/met7060228.
- [190] B. Song, S. Dong, H. Liao, C. Coddet, Process parameter selection for selective laser melting of Ti6Al4V based on temperature distribution simulation and experimental sintering, *Int. J. Adv. Manuf. Technol.* 61 (2012) 967–974. doi:10.1007/s00170-011-3776-6.
- [191] J.P. Davim, C. Oliveira, A. Cardoso, Predicting the geometric form of clad in laser cladding by powder using multiple regression analysis (MRA), 29 (2008) 554–557. doi:10.1016/j.matdes.2007.01.023.
- [192] Y. Fu, A. Loredó, B. Martín, A.B. Vannes, A theoretical model for laser and powder particles interaction during laser cladding, 128 (2002) 106–112.

Appendices

Appendix A

Analytical analysis of temperature distribution

A semi-infinite solid geometry has been taken which extends to infinity in all direction except one direction. The used material was Ti6Al4V. The constant material properties at room temperature was used to calculate the temperature distribution, given in Fig. 6.4 and 6.5. The Analytical solution for the transient heat conduction of a semi-infinite solid with a constant heat flux is [163].

$$T(y, t) - T_i = \frac{2Q \left(\frac{\alpha t}{\pi}\right)^{\frac{1}{2}}}{k} \exp\left(-\frac{y^2}{4\alpha t}\right) - \frac{yQ}{k} \operatorname{erfc}\left(\frac{y}{2\sqrt{\alpha t}}\right) \dots \dots \dots (A1)$$

where, T_i is the initial temperature, Q is the constant heat flux, k is the thermal conductivity, α is the thermal diffusivity (0.25), t is the time and y is the distance.

A finite element model was performed using the same geometry of analytical model. This geometry was meshed using transitional meshing method. After that, same material properties of analytical model was applied in this model. In this case, a constant heat flux was applied on the surface of the geometry using Eq. C3 in appendix C.

The results from the analytical and the numerical models have been compared. Temperature distribution from the surface to 5 mm depth has been shown in Fig. A1 for both cases. On the surface, the temperature was 200 K lower in case of the finite element model than the analytical model.

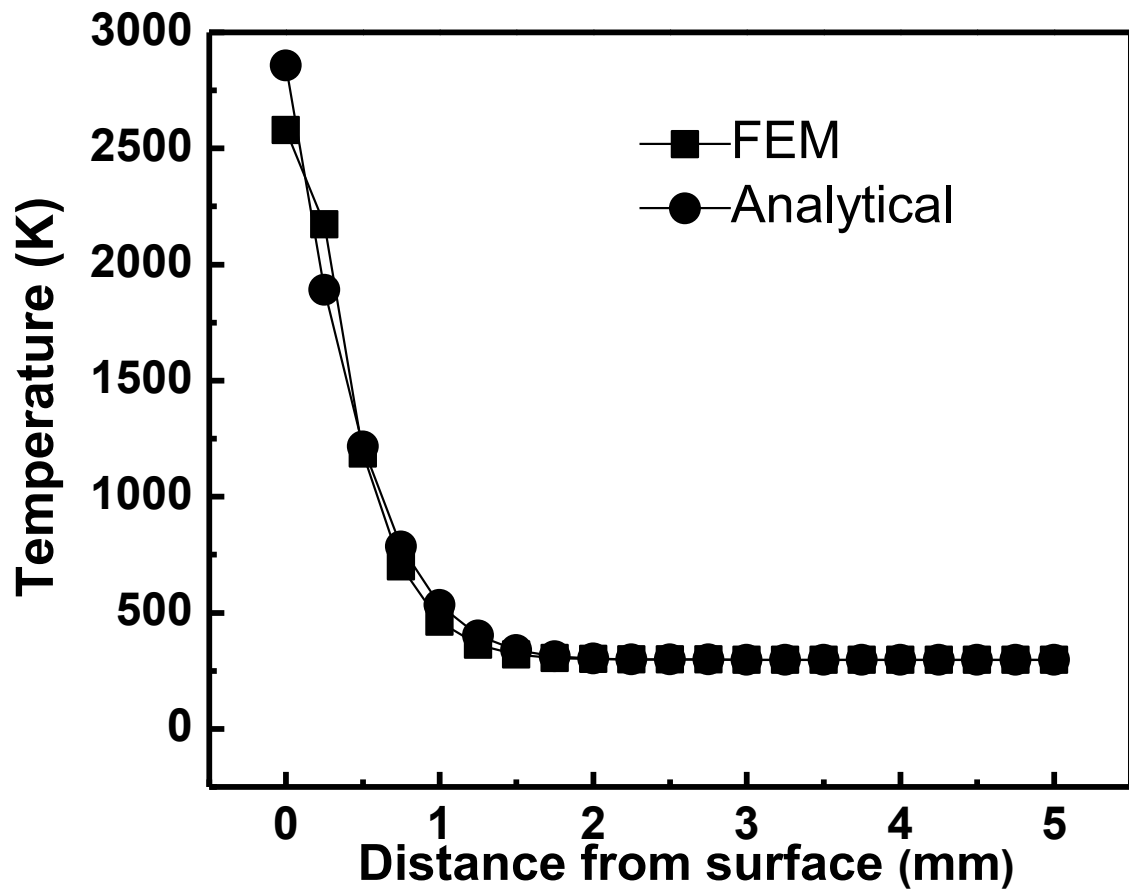


Fig. A1 The comparison of the temperature distribution between the analytical and the FEM result.

Appendix B

Model set-up of analytical model of residual stress

A simplified model was adopted to calculate the residual stress as shown in Fig. 4.1 considering the elastic and the thermal strain. σ is the normal tensile residual stress [163,164]. α , E and h are defined as the thermal expansion coefficient, Young's modulus and the thickness. The subscript c and s represents the clad and the substrate respectively. T_r is the room temperature, T_0 is the preheating temperature of the substrate and T_{mc} is melting temperature or operating temperature of cladding materials respectively. In the Laser Cladding process, the operating temperature should be equal or more than the melting temperature of cladding materials. If the clad and the substrate contract freely, the thermal contraction are $\alpha_c l(T_{mc} - T_r)$ and $\alpha_s l(T_0 - T_r)$ correspondingly. The higher thermal strain of cladding material was assumed than the substrate material. The induced elastic strains are σ_c/E_c and σ_s/E_s due to residual stress of clad and the substrate. But, the coating and the substrate are connected with a metallurgical bonding. So the actual contraction at the interface of the clad and the substrate is

$$\alpha_c l(T_{mc} - T_r) - \sigma_c l/E_c = \alpha_s l(T_0 - T_r) + \sigma_s l/E_s \dots \dots \dots (B1)$$

The uniform stress distribution is assumed in the clad and the substrate while the height of the clad was lower than the height of the substrate. From the internal force balance

$$h_s \sigma_s = h_c \sigma_c \dots \dots \dots (B2)$$

Here h_s and h_c are the height of the substrate and the clad. σ_c and σ_s are the tensile residual stress of the clad and the substrate. From Eq. B1 and B2, the generated stress in the clad can be derived

$$\sigma_c = \frac{h_s E_s E_c [\alpha_c (T_{mc} - T_r) - \alpha_s (T_0 - T_r)]}{h_s E_s + h_c E_c} \dots \dots \dots (B3)$$

Table B1. Notations of the analytical model are tabulated.

Parameters	Substrate	Clad
Coefficient of thermal expansion (K^{-1})	α_s	α_c
Young's Modulus (MPa)	E_s	E_c
Melting temperature of the clad (K)		T_{mc}
Substrate temperature (K)	T_0	
Height (m)	h_s	h_c
Room temperature (K)	T_r	T_r

Appendix C

Assumptions, boundary conditions and governing equation of finite element model

In finite element model, the classical heat conduction theory is applied in order to predict temperature distributions. In this model, material properties of the clad and the substrate are assumed isotropic. The interaction of liquid metal is ignored as solidification happens within a fraction of second. The phenomena of chemical reaction and stir convection in the melt pool was ignored.

The initial temperature was set up to 293 K as room temperature at the beginning of the process. This is the initial condition. The heat loss due to convection and radiation of the laser beam was applied on the surface of the model. In the structural analysis, transient temperature from the previous thermal analysis was transferred as static temperature load in every node. The same mesh is used for the mechanical analysis. The substrate is assumed as stress free before starting the process. A rigid body constrain was applied in the middle of bottom surface. Also, the vertical movement of the substrate was restricted. The indirect coupling of thermo-structural analysis has been done. The initial boundary condition can be stated in terms of stress-strain response in Eqs. C1-C2.

$$\sigma(X, Y, 0) = 0 \dots \dots \dots (C1)$$

$$\varepsilon(X, Y, 0) = 0 \dots \dots \dots (C2)$$

The Governing equations of the 2D and the 3D transient heat conduction model are expressed in Eqs C3-C4.

$$\frac{\rho \partial(C_p T)}{\partial t} = \frac{\partial^2(kT)}{\partial x^2} + \frac{\partial^2(kT)}{\partial y^2} + Q \dots \dots \dots (C3)$$

and

$$\frac{\rho \partial(C_p T)}{\partial t} = \frac{\partial^2(kT)}{\partial x^2} + \frac{\partial^2(kT)}{\partial y^2} + \frac{\partial^2(kT)}{\partial z^2} + Q \dots \dots \dots (C4)$$

where, ρ (kgm^{-3}) is the density, C_p ($\text{Jkg}^{-1}\text{K}^{-1}$) is the specific heat, t (s) is the time, T is the time dependent temperature and k ($\text{Wm}^{-1}\text{K}^{-1}$) is the thermal conductivity. X , Y and Z are the global coordinate. Q is the laser heat input.

The heat input Q was calculated from the following Eq. C5 and Eq. C6 for the 2D [190] and 3D [71] thermal model respectively.

The heat input Q for the 2D thermal model is expressed by the following equation

$$Q_{(X,Y)} = \frac{\eta P}{\pi R^2} \exp\left(\frac{-2r^2}{R^2}\right) \dots \dots \dots (C5)$$

$$\text{here } r = \sqrt{X^2 + Y^2}$$

where, P is the power of laser beam, R is the laser beam radius, η is the absorption coefficient of material and r is the distribution of heat source. X , Y and Z are the Cartesian coordinate. The absorption coefficient of Ti6Al4V is 0.25.

A Gaussian distribution of heat input Q in radial direction and exponential decay in depth is given in the following Eq. C6 as a 3D volumetric heat source for the 3D thermal model

$$Q_{(X,Y,Z)} = \frac{6\eta P}{\pi\sqrt{\pi}R^3} \exp(-3r^2/R^2) \dots \dots \dots (C6)$$

$$\text{here } r = \sqrt{X^2 + Y^2 + Z^2}$$

where, P is the power of laser beam, R is the laser beam radius, η is the absorption coefficient of material and r is the distribution of heat source. X , Y and Z are the Cartesian coordinate. The absorption coefficient of Ti6Al4V is 0.25.

The governing equation of predicting strain in the process is,

$$\varepsilon = \varepsilon^{el} + \varepsilon^{pl} + \varepsilon^{th} + \varepsilon^{Trp} \quad (C7)$$

Where, ε^{el} , ε^{pl} , ε^{th} and ε^{Trp} are elastic, plastic, thermal and phase transformation strain respectively.

The developed code for 2D and 3D models are given below.

The code of 2D model

```
/PREP7
!!!!!!!!!!!! Plane 55 !!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!*
ET,1,PLANE 55
!*
!!!!!!!!!!!! Material properties !!!!!!!!!!!!!!!!!!!!!
!*
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,KXX,1,,28.6
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,C,1,,658
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,DENS,1,,7835

!!!!!!!!!!!! Modelling !!!!!!!!!!!!!!!!!!!!!!!!!!!!!
RECTNG,0,0.012,0,0.003,
RECTNG,0,0.012,0.003,0.004,
RECTNG,0,0.012,0.004,0.0045,
RECTNG,0,0.005,0.0045,0.005,
RECTNG,0.005,0.007,0.0045,0.005,
RECTNG,0.007,0.012,0.0045,0.005,
RECTNG,0.005607,0.006393,0.005,0.005169,
!!!!!!!!!!!! Gluing the model !!!!!!!!!!!!!!!!!!!!!!!!!!!!!
FLST,2,2,5,ORDE,2
FITEM,2,1
FITEM,2,-2
AGLUE,P51X
FLST,2,2,5,ORDE,2
FITEM,2,3
FITEM,2,8
AGLUE,P51X
FLST,2,4,5,ORDE,2
FITEM,2,3
FITEM,2,-6
AGLUE,P51X
FLST,2,2,5,ORDE,2
FITEM,2,8
FITEM,2,11
AGLUE,P51X
FLST,2,2,5,ORDE,2
FITEM,2,9
FITEM,2,11
```

```

AGLUE,P51X
FLST,2,2,5,ORDE,2
FITEM,2,10
FITEM,2,-11
AGLUE,P51X
FLST,2,3,5,ORDE,2
FITEM,2,8
FITEM,2,-10
AGLUE,P51X
FLST,2,2,5,ORDE,2
FITEM,2,7
FITEM,2,9
AGLUE,P51X
FLST,5,2,4,ORDE,2
FITEM,5,25
FITEM,5,27
CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,,_Y

```

!!!!!!!!!!!! Meshing the model !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

```

FLST,5,2,4,ORDE,2
FITEM,5,25
FITEM,5,27
CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1, , ,17, , , ,1
!*
FLST,5,2,4,ORDE,2
FITEM,5,26
FITEM,5,28
CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1, , ,5, , , ,1
!*
FLST,5,2,4,ORDE,2
FITEM,5,11
FITEM,5,13
CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*

```

```

LESIZE,_Y1, , ,12, , , ,1
!*
FLST,5,1,4,ORDE,1
FITEM,5,29
CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1, , ,35, , , ,1
!*

```

```

FLST,5,4,4,ORDE,4
FITEM,5,8
FITEM,5,14
FITEM,5,18
FITEM,5,32
CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1, , ,10, , , ,1
!*

```

```

FLST,5,4,4,ORDE,4
FITEM,5,7
FITEM,5,15
FITEM,5,31
FITEM,5,33
CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1, , ,40, , , ,1
!*

```

```

FLST,5,1,4,ORDE,1
FITEM,5,9
CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1, , ,85, , , ,1
!*
FLST,5,1,4,ORDE,1
FITEM,5,3

```

```

CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1, , ,60, , , ,1
!*
FLST,5,1,4,ORDE,1
FITEM,5,1
CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1, , ,40, , , ,1
!*
FLST,5,4,4,ORDE,3
FITEM,5,2
FITEM,5,4
FITEM,5,-6
CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1, , ,7, , , ,1
!*
FLST,5,2,4,ORDE,2
FITEM,5,10
FITEM,5,12
CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1, , ,5, , , ,1
!*

!*
MSHKEY,0
FLST,5,7,5,ORDE,6
FITEM,5,1
FITEM,5,-3
FITEM,5,7
FITEM,5,-8
FITEM,5,10
FITEM,5,-11
CM,_Y,AREA
ASEL, , , ,P51X
CM,_Y1,AREA

```

```

CHKMSH,'AREA'
CMSEL,S,_Y
!*
AMESH,_Y1
!*
CMDELE,_Y
CMDELE,_Y1
CMDELE,_Y2
!*

```

```

!!!!!!!!!!!!!! solution !!!!!!!!!!!!!!!

```

```

FINISH
/SOL
ANTYPE,4                      !Specify analysis type,4-transient
TRNOPT,FULL                    !specify the transient option
TUNIF,300,                     !Assing a uniform temperature at all nodes
timint,on                      !turns on transient effect
SOLCONTROL,on                  !Specifies whether to use optimized nonlinear
solution defaults and some enhanced internal solution algorithms
NROPT,FULL,,ON                !Specifies the Newton-Raphson options in a
static or full transient analysis
pred,on                        !Activates a predictor in a nonlinear analysis.
neqit,400                      !Specifies the maximum number of equilibrium iterations
for nonlinear analyses
autots,0                       !Specifies whether to use automatic time stepping or
load stepping
eqslv,SPARSE                   !Specifies the type of equation solver
KBC,0                          !Specifies ramped or stepped loading within a load step,
0 means rapped
LNSRCH,1                       !Activates a line search to be used with Newton-
Raphson
ALLSEL,ALL

```

```

FLST,2,54,1,ORDE,35
FITEM,2,1796
FITEM,2,1799
FITEM,2,-1819
FITEM,2,1824
FITEM,2,-1825
FITEM,2,1828
FITEM,2,-1829
FITEM,2,1832
FITEM,2,-1833
FITEM,2,1836
FITEM,2,-1837
FITEM,2,1840
FITEM,2,-1841
FITEM,2,1844
FITEM,2,-1845
FITEM,2,1848

```

```

FITEM,2,-1849
FITEM,2,1852
FITEM,2,-1853
FITEM,2,1856
FITEM,2,-1857
FITEM,2,1860
FITEM,2,-1861
FITEM,2,1864
FITEM,2,-1865
FITEM,2,1868
FITEM,2,-1869
FITEM,2,1872
FITEM,2,-1873
FITEM,2,1876
FITEM,2,-1877
FITEM,2,1880
FITEM,2,-1881
FITEM,2,1884
FITEM,2,-1885
/GO
!*
SF,P51X,HFLUX,2.4e8
NSUBST,50
TIME,0.053
outres,all,all
/sol
allsel
SOLVE
SFDELE,ALL,ALL
SFDELE,ALL,ALL,ALL

```

```

!!!!!!!!!!!!cooling!!!!!!!!!!
CSYS,0           !Activates a previously defined coordinate system
TIME,0.053+6     ! 6 sec ei cool hoe jasse
NSUBST,100
outres,all,all
solve

```

```

!!!!!!!!!!!!!!stress model!!!!!!!!!!
/PREP7
ETCHG,TTS

```

```

/SOL
FLST,2,1,1,ORDE,1
FITEM,2,22
!*
/GO
D,P51X, ,0, , , ,UX,UY, , , ,

```

!!!!!!!!!!rotation!!!!!!!!!!!!!!

```
FLST,2,1,1,ORDE,1
FITEM,2,22
!*
/GO
F,P51X,FX,0
FLST,2,1,1,ORDE,1
FITEM,2,22
!*
/GO
F,P51X,FY,0
```

!!!!!!!!!!bottom and side in y!!!!!!!!!!!!!!

```
FLST,2,98,1,ORDE,19
FITEM,2,1
FITEM,2,-21
FITEM,2,23
FITEM,2,-49
FITEM,2,109
FITEM,2,-114
FITEM,2,879
FITEM,2,-886
FITEM,2,971
FITEM,2,-976
FITEM,2,1886
FITEM,2,1926
FITEM,2,1966
FITEM,2,-1974
FITEM,2,2326
FITEM,2,2366
FITEM,2,-2375
FITEM,2,2766
FITEM,2,-2773
!*
/GO
D,P51X, ,0, , , ,UY, , , , ,
```

!!!!!!!!!!top in y!!!!!!!!!!!!!!

```
FLST,2,52,1,ORDE,4
FITEM,2,1430
FITEM,2,-1441
FITEM,2,1926
FITEM,2,-1965
!*
/GO
D,P51X, ,0, , , ,UY, , , , ,
```

```

FLST,2,52,1,ORDE,6
FITEM,2,1391
FITEM,2,1402
FITEM,2,-1412
FITEM,2,2366
FITEM,2,2376
FITEM,2,-2414
!*
/GO
D,P51X,,0,, , , ,UY, , , , ,

```

```

!!!!!!!!!!!!!!!!!!!!solution set!!!!!!!!!!!!!!!!!!!!

```

```

/SOL
ANTYPE,static, new           !Specify analysis type,1-static
TUNIF,300,                   !Assing a uniform temperature at all nodes
!TREF,300,                   !Define the reference temperature
SOLCONTROL,on                !Specifies whether to use optimized nonlinear
solution defaults and some enhanced internal solution algorithms
eqslv,SPARSE                 !Specifies the type of equation solver
KBC,0                        !Specifies ramped or stepped loading within a load step,
0 means rapped
ALLSEL,ALL
!
time, 0.053
!NSUBST,10
ldread, temp,,, 0.053, , Hstress_uncouple, 'rth'
Solve

```

```

time, 0.053+6
ldread, temp,,, 0.053+6, , Hstress_uncouple, 'rth'
Solve

```

The code of 3D Ti6Al4V/Ti6Al4V model

```
/PREP7
!*
et,1,70
BLOCK,0,0.005,0,0.003,0,0.016,
local,11,1, 0.0025,0.00289, , , ,
CYL4,0.0025,0.00289,0.00061,0, ,180,0.016
VSBV, 2, 1
BLOCK,0,0.005,0,0.003,0,0.016,
VPLOT
vlist, all
FLST,2,2,6,ORDE,2
FITEM,2,1
FITEM,2,3
VGLUE,P51X
WPSTYLE,,,,,,,,0
FLST,2,1,8 !!!!!!!forming the working plane
FITEM,2,0.25E-02,0,0
WPAVE,P51X
wprotar,,,-90
FLST,2,2,6,ORDE,2
FITEM,2,2
FITEM,2,-3
VSBW,P51X

FLST,2,2,6,ORDE,2
FITEM,2,4
FITEM,2,-5
VDELE,P51X, , ,1

FLST,2,1,8
FITEM,2,0.31E-02,0,0
WPAVE,P51X
FLST,2,2,6,ORDE,2
FITEM,2,1
FITEM,2,6
VSBW,P51X
FLST,2,1,8
FITEM,2,0.35E-02,0,0
WPAVE,P51X
VSBW, 3
FLST,2,1,8
FITEM,2,0.4E-02,0,0
WPAVE,P51X
VSBW, 4
FLST,2,1,8
FITEM,2,0.25E-02,0.2E-02,0
```



```
LESIZE,_Y1, , ,100, , , ,1
!*

```

```
FLST,5,6,4,ORDE,5
FITEM,5,5
FITEM,5,18
FITEM,5,-20
FITEM,5,23
FITEM,5,47
CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*

```

```
!LESIZE,_Y1, , ,15, , , ,1
!LESIZE,_Y1, , ,5, , , ,1
!LESIZE,_Y1, , ,10, , , ,1
LESIZE,_Y1, , ,20, , , ,1
!*

```

```
FLST,5,3,4,ORDE,3
FITEM,5,25
FITEM,5,46
FITEM,5,72
CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*

```

```
!LESIZE,_Y1, , ,5, , , ,1
!LESIZE,_Y1, , ,10, , , ,1
LESIZE,_Y1, , ,20, , , ,1
!LESIZE,_Y1, , ,25, , , ,1
!LESIZE,_Y1, , ,30, , , ,1
!LESIZE,_Y1, , ,35, , , ,1
!LESIZE,_Y1, , ,40, , , ,1
!LESIZE,_Y1, , ,45, , , ,1
!LESIZE,_Y1, , ,60, , , ,1
!LESIZE,_Y1, , ,100, , , ,1
!*

```

```
FLST,5,1,4,ORDE,1
FITEM,5,65
CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*

```

```
!LESIZE,_Y1, , ,15, , , ,1
LESIZE,_Y1, , ,5, , , ,1

```

!*
!

FLST,5,1,4,ORDE,1
FITEM,5,63
CM,_Y,LINE
LSEL,,,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
!LESIZE,_Y1,,,10,,,,,1
LESIZE,_Y1,,,5,,,,,1
!*
!

FLST,5,4,4,ORDE,4
FITEM,5,90
FITEM,5,-91
FITEM,5,95
FITEM,5,97
CM,_Y,LINE
LSEL,,,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1,,,5,,,,,1
!*
!

FLST,5,1,4,ORDE,1
FITEM,5,93
CM,_Y,LINE
LSEL,,,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1,,,4,,,,,1
!*
!

FLST,5,5,4,ORDE,5
FITEM,5,8
FITEM,5,14
FITEM,5,39
FITEM,5,78
FITEM,5,83
CM,_Y,LINE
LSEL,,,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1,,,5,,,,,1

!*

FLST,5,4,4,ORDE,4
FITEM,5,33
FITEM,5,-34
FITEM,5,70
FITEM,5,84
CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1, , ,10, , , ,1
!*

FLST,5,4,4,ORDE,4
FITEM,5,44
FITEM,5,-45
FITEM,5,74
FITEM,5,87
CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1, , ,10, , , ,1
!*

FLST,5,4,4,ORDE,4
FITEM,5,15
FITEM,5,38
FITEM,5,60
FITEM,5,79
CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1, , ,5, , , ,1
!*

FLST,5,3,4,ORDE,3
FITEM,5,11
FITEM,5,30
FITEM,5,41
CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,,_Y

```
!*  
LESIZE,_Y1, , ,100, , , ,1  
!*
```

```
FLST,5,6,4,ORDE,6  
FITEM,5,1  
FITEM,5,-2  
FITEM,5,6  
FITEM,5,-7  
FITEM,5,17  
FITEM,5,24  
CM,_Y,LINE  
LSEL, , , ,P51X  
CM,_Y1,LINE  
CMSEL,,_Y
```

```
!*  
!LESIZE,_Y1, , ,15, , , ,1  
!LESIZE,_Y1, , ,5, , , ,1  
!LESIZE,_Y1, , ,10, , , ,1  
LESIZE,_Y1, , ,20, , , ,1  
!*
```

```
FLST,5,3,4,ORDE,3  
FITEM,5,16  
FITEM,5,22  
FITEM,5,71  
CM,_Y,LINE  
LSEL, , , ,P51X  
CM,_Y1,LINE  
CMSEL,,_Y
```

```
!*  
!LESIZE,_Y1, , ,5, , , ,1  
!LESIZE,_Y1, , ,10, , , ,1  
LESIZE,_Y1, , ,20, , , ,1  
!LESIZE,_Y1, , ,25, , , ,1  
!LESIZE,_Y1, , ,30, , , ,1  
!LESIZE,_Y1, , ,35, , , ,1  
!LESIZE,_Y1, , ,40, , , ,1  
!LESIZE,_Y1, , ,45, , , ,1  
!LESIZE,_Y1, , ,60, , , ,1  
!LESIZE,_Y1, , ,100, , , ,1  
!*
```

```
FLST,5,1,4,ORDE,1  
FITEM,5,64  
CM,_Y,LINE  
LSEL, , , ,P51X  
CM,_Y1,LINE  
CMSEL,,_Y  
!*
```

```
!LESIZE,_Y1, , ,15, , , ,1
LESIZE,_Y1, , ,5, , , ,1
!*

```

```
FLST,5,1,4,ORDE,1
FITEM,5,62
CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
!LESIZE,_Y1, , ,10, , , ,1
LESIZE,_Y1, , ,5, , , ,1
!*

```

```
FLST,5,8,4,ORDE,8
FITEM,5,31
FITEM,5,-32
FITEM,5,42
FITEM,5,-43
FITEM,5,69
FITEM,5,73
FITEM,5,82
FITEM,5,86
CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1, , ,10, , , ,1
!*

```

```
FLST,5,4,4,ORDE,4
FITEM,5,88
FITEM,5,-89
FITEM,5,94
FITEM,5,96
CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1, , ,5, , , ,1
!*

```

```
FLST,5,1,4,ORDE,1
FITEM,5,92
CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE

```

```

CMSEL,,_Y
!*
LESIZE,_Y1,,4,,,,1
!*

```

```

FLST,5,5,4,ORDE,5
FITEM,5,3
FITEM,5,-4
FITEM,5,37
FITEM,5,76
FITEM,5,81
CM,_Y,LINE
LSEL,,,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1,,,5,,,,1
!*

```

```

FLST,5,4,4,ORDE,4
FITEM,5,12
FITEM,5,-13
FITEM,5,58
FITEM,5,77
CM,_Y,LINE
LSEL,,,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1,,,5,,,,1
!*

```

```

FLST,5,13,6,ORDE,6
FITEM,5,1
FITEM,5,-6
FITEM,5,9
FITEM,5,11
FITEM,5,13
FITEM,5,-17
CM,_Y,VOLU
VSEL,,,P51X
CM,_Y1,VOLU
CHKMSH,'VOLU'
CMSEL,S,_Y
!*
MSHAPE,0,3d
MSHKEY,1
VMESH,_Y1
MSHKEY,0
!*

```

CMDELE,_Y
CMDELE,_Y1
CMDELE,_Y2
!*
.

!!!!!!!!!!!!!!materials properties!!!!!!!!!!!!!!

MP,DENS,1,4440 !density
mptemp,1,20,100,200,300,400,500,600,700,1000,1600,1660,1670,1800,2800
mpdata,kxx,1,1,6.8,7.4,8.7,9.8,10.3,11.8,12.8,13.5,22.3,27.5,27.5,27.5,27.5
!thermal conductivity
mptemp,1,20,100,200,300,400,500,600,700,1057.4266,1567.8054,1635.6063,166
9.3114,1919.9058
mpdata,c,1,1,611,624,653,674,691,703,710,712,759.8014,828.1918,970.0204082
,1118.2786,1130.169

!!!!!!!!!!!!!!film coefficient!!!!!!!!!!!!
!*
.

MPTEMP,,,,,,,,,
MPTEMP,1,20
MPTEMP,2,100
MPTEMP,3,200
MPTEMP,4,300
MPTEMP,5,400
MPTEMP,6,500
MPTEMP,7,600
MPTEMP,8,700
MPTEMP,9,800
MPTEMP,10,900
MPTEMP,11,1000
MPTEMP,12,1200
MPTEMP,13,1400
MPTEMP,14,1600
MPTEMP,15, 1800
MPTEMP,16,2000
MPTEMP,17,2200
MPTEMP,18,2400
MPTEMP,19,2600
MPTEMP,20,2800
MPTEMP,21,3000
MPTEMP,22,3200
MPDATA,HF,1,,0.1053
MPDATA,HF,1,,1.4057
MPDATA,HF,1,,4.2908
MPDATA,HF,1,,8.2423
MPDATA,HF,1,,13.0978
MPDATA,HF,1,,18.76
MPDATA,HF,1,,25.1598
MPDATA,HF,1,,32.2471

MPDATA,HF,1,,39.9814
 MPDATA,HF,1,,48.32
 MPDATA,HF,1,,57.26
 MPDATA,HF,1,,76.8
 MPDATA,HF,1,,98.4350
 MPDATA,HF,1,,122.0440
 MPDATA,HF,1,,147.5272
 MPDATA,HF,1,,174.8001
 MPDATA,HF,1,,203.7905
 MPDATA,HF,1,,234.4356
 MPDATA,HF,1,,266.6800
 MPDATA,HF,1,,300.4747
 MPDATA,HF,1,,335.7752
 MPDATA,HF,1,,372.5417

!!!!!!!!!!!!!!!!!!!!!!!!!!!!Thermal solution

FINISH

/SOL

nropt,full

ANTYPE,4

!Specify analysis type,4-transient

TRNOPT,FULL

!specify the transient option

TUNIF,20,

!Assing a uniform temperature at all nodes

TREF,20,

!Define the reference temperature

timint,on

!turns on transient effect

SOLCONTROL,on

!Specifies whether to use optimized nonlinear

solution defaults and some enhanced internal solution algorithms

NROPT,FULL,,ON

!Specifies the Newton-Raphson options in a

static or full transient analysis

pred,on

!Activates a predictor in a nonlinear analysis.

neqit,40

!Specifies the maximum number of equilibrium iterations

for nonlinear analyses

autots,0

!Specifies whether to use automatic time stepping or

load stepping

eqslv,SPARSE

!Specifies the type of equation solver

!SSTIF,ON

! did not understand

!NSUBST,1

!Specifies the number of substeps to be taken this

load step

!EQSLV,-1

!what does it mean?

KBC,0

!Specifies ramped or stepped loading within a load step,

0 means rapped

LNSRCH,1

!Activates a line search to be used with Newton-

Raphson

ALLSEL,ALL

!M_T=0

!!!!!!!!!!!!!!!!!!!!!!temperature!!!!!!!!!!!!!!

!!!!!!!!!!!!!!apply convection !!!!!!!!!!!!!!!

FLST,5,6,5,ORDE,6

FITEM,5,1

FITEM,5,-2
FITEM,5,11
FITEM,5,13
FITEM,5,24
FITEM,5,29
ASEL,S, , ,P51X
NSLA,S,1
SF,ALL,CONV,-1,20

!!!!!!!!!!!!!!apply convection !!!!!!!!!!!!!!!

FLST,5,33,5,ORDE,26

FITEM,5,1
FITEM,5,-3
FITEM,5,5
FITEM,5,10
FITEM,5,-11
FITEM,5,13
FITEM,5,-15
FITEM,5,19
FITEM,5,-20
FITEM,5,24
FITEM,5,-26
FITEM,5,29
FITEM,5,40
FITEM,5,-42
FITEM,5,48
FITEM,5,50
FITEM,5,54
FITEM,5,-55
FITEM,5,57
FITEM,5,-58
FITEM,5,60
FITEM,5,-61
FITEM,5,64
FITEM,5,-66
FITEM,5,69
FITEM,5,-72
ASEL,S, , ,P51X
NSLA,S,1
SF,ALL,CONV,-1,20

!!!!!!!!!!!!!!ekill!!!!!!!!!!!!!!

local,12,0,0.0025,0.003, , , ,
!esel,s,cent,x,-0.00059,0.00059
esel,s,cent,x,0,0.00059
esel,r,cent,y,0,0.00055
esel,r,cent,z,0,0.016
CM,clad,ELEM
ekill,all

```
esel,s,elem, ,clad
nsle,s
CM,clad_node,node
eplot
```

```
!!!!!!!!!!!!starting of do loop!!!!!!!!!!!!!!
```

```
*do,i,1,27,1
```

```
!*SET,a,3
```

```
*SET,a,2
```

```
*SET,sb,0.0012/a
```

```
*SET,tm,0.103/a
```

```
!*SET,i,1
```

```
*SET,XX,(i-1)*sb
```

```
local,13,0,0.0025,0.003,XX, , ,
```

```
NSEL,S,LOC,Z,0,sb
```

```
!NSEL,S,LOC,Z,-0.0006,0.0006
```

```
!NSEL,R,LOC,X,-0.0006,0.0006
```

```
NSEL,R,LOC,X,0,0.0006
```

```
NSEL,R,LOC,Y,0,0.00055
```

```
cm,cur_node,node
```

```
esln,s
```

```
ealive,all
```

```
!!!!application of heat source!!!!!!!!!!!!
```

```
local,14,0,0.0025,0.003,XX, , ,
```

```
!local,14,0,0.0025,0.00325,XX, , ,
```

```
!local,14,0,0.0025,0.0028,XX, , ,
```

```
NSEL,S,LOC,Z,-0.0021,0.0021
```

```
NSEL,R,LOC,X,-0.0021,0.0021
```

```
NSEL,R,LOC,Y,-0.0021,0.0021
```

```
!NSEL,R,LOC,Y,-0.0021,0
```

```
!NSEL,R,LOC,Y,0,0.0021
```

```
cm,cur_node,node
```

```
*DEL,hh
```

```
*DEL,_FNCNAME
```

```
*DEL,_FNCMTID
```

```
*DEL,_FNCCSYS
```

```
*SET,_FNCNAME,'hh'
```

```
*SET,_FNCCSYS,14
```

```
!/input,'hh',func,",:FUNC,1
```

```
*DIM,%_FNCNAME%,TABLE,6,18,1,,,_%FNCCSYS%
```

```
!
```

```
! Begin of equation: 4.7122e11*exp(-6.1224e6*({x}^2+{y}^2+{z}^2))
```

```
_%FNCNAME%(0,0,1)= 0.0, -999
```

```

%_FNCNAME%(2,0,1)= 0.0
%_FNCNAME%(3,0,1)= 0.0
%_FNCNAME%(4,0,1)= 0.0
%_FNCNAME%(5,0,1)= 0.0
%_FNCNAME%(6,0,1)= 0.0
%_FNCNAME%(0,1,1)= 1.0, -1, 0, 0, 0, 0, 0
%_FNCNAME%(0,2,1)= 0.0, -2, 0, 1, 0, 0, -1
%_FNCNAME%(0,3,1)= 0, -3, 0, 1, -1, 2, -2
%_FNCNAME%(0,4,1)= 0.0, -1, 0, 6.1224e6, 0, 0, -3
%_FNCNAME%(0,5,1)= 0.0, -2, 0, 1, -3, 3, -1
%_FNCNAME%(0,6,1)= 0.0, -1, 0, 2, 0, 0, 2
%_FNCNAME%(0,7,1)= 0.0, -3, 0, 1, 2, 17, -1
%_FNCNAME%(0,8,1)= 0.0, -1, 0, 2, 0, 0, 3
%_FNCNAME%(0,9,1)= 0.0, -4, 0, 1, 3, 17, -1
%_FNCNAME%(0,10,1)= 0.0, -1, 0, 1, -3, 1, -4
%_FNCNAME%(0,11,1)= 0.0, -3, 0, 2, 0, 0, 4
%_FNCNAME%(0,12,1)= 0.0, -4, 0, 1, 4, 17, -3
%_FNCNAME%(0,13,1)= 0.0, -3, 0, 1, -1, 1, -4
%_FNCNAME%(0,14,1)= 0.0, -1, 0, 1, -2, 3, -3
%_FNCNAME%(0,15,1)= 0.0, -1, 7, 1, -1, 0, 0
%_FNCNAME%(0,16,1)= 0.0, -2, 0, 4.7122e11, 0, 0, -1
%_FNCNAME%(0,17,1)= 0.0, -3, 0, 1, -2, 3, -1
%_FNCNAME%(0,18,1)= 0.0, 99, 0, 1, -3, 0, 0
! End of equation: 4.7122e11*exp(-6.1224e6*({x}^2+{y}^2+{z}^2))
!-->

```

```

BF,all,HGEN,%hh%
time,i*tm !!!!!!!700mm/min
NSUBST,1
outres,all,all

```

```

/sol
allsel
solve

```

```

BFDELE,all,HGEN !!!!!!!removing heat source

```

```

OUTRES,ALL,ALL,
esel,s,live
eplot
*ENDDO

```

```

!SFDELE,ALL,ALL

```

```

/sol
allsel
CSYS,0 !Activates a previously defined coordinate system
!TIME,1.3905+500

```

```

!TIME,1.3905+2500

```

TIME,1.3905+8000
NSUBST,50

solve
esel,s,live
eplot
FINISH

!!!!!!!!!!!!!!stress model!!!!!!!!!!!!
FINISH
/PREP7
ETCHG,TTS
FINISH
!

/PREP7
!*
KEYOPT,1,2,0
KEYOPT,1,3,0
KEYOPT,1,6,0
KEYOPT,1,8,0
!*
!

!!!!!!!!!!!!!!elastic modulus and poisson ratio!!!!!!!!!!!!!!
MPTEMP,,,,,,,,
MPTEMP,1,20
MPTEMP,2,100
MPTEMP,3,200
MPTEMP,4,315
MPTEMP,5,430
MPTEMP,6,540
MPTEMP,7,1650
MPTEMP,8,2800
MPDATA,EX,1,,1.14e11
MPDATA,EX,1,,1.09e11
MPDATA,EX,1,,1e11
MPDATA,EX,1,,9.3e10
MPDATA,EX,1,,8.4e10
MPDATA,EX,1,,5.7e10
MPDATA,EX,1,,1e8
MPDATA,EX,1,,1e8
MPDATA,PRXY,1,,0.342
MPDATA,PRXY,1,,0.342
MPDATA,PRXY,1,,0.342
MPDATA,PRXY,1,,0.342
MPDATA,PRXY,1,,0.342
MPDATA,PRXY,1,,0.342
MPDATA,PRXY,1,,0.49
MPDATA,PRXY,1,,0.49

!!!!!!!!!!!!thermal expansion coefficient!!!!!!

```
MPTEMP,,,,,,,,
MPTEMP,1,20
MPTEMP,2,100
MPTEMP,3,200
MPTEMP,4,315
MPTEMP,5,430
MPTEMP,6,540
MPTEMP,7,1650
MPTEMP,8,2800
UIMP,1,REFT,,,
MPDATA,CTEX,1,,8.2e-6
MPDATA,CTEX,1,,9.2e-6
MPDATA,CTEX,1,,9.9e-6
MPDATA,CTEX,1,,1.05e-5
MPDATA,CTEX,1,,1.1e-5
MPDATA,CTEX,1,,1.14e-5
MPDATA,CTEX,1,,2.01e-5
MPDATA,CTEX,1,,2.01e-5
```

/PREP7

!!!!!!!!!!!!yeild stress and tangent modulus!!!!!!

```
TB,BISO,1,6,2,
TBTEMP,20
TBDATA,,1061e6,6.31e9,,,
TBTEMP,370
TBDATA,,651e6,5.01e9,,,
TBTEMP,480
TBDATA,,548e6,4.67e9,,,
TBTEMP,825
TBDATA,,548e6,4.76e9,,,
TBTEMP,875
TBDATA,,400e6,3.48e9,,,
TBTEMP,950
TBDATA,,400e6,1.67e9,,,
```

/SOLU

!!!!!!!!!!!!initial condition!!!!!!!!!!!!!!

```
local,15,0,0.0025,0,0, , ,
NSEL,S,LOC,Z,0,0.016
NSEL,A,LOC,X,0.0025
NSEL,R,LOC,Y,0,0.0001
D,all,UY,0
```

!!!!!!!!!!!!at the middle of symmetry only for all direction!!!!!!!!!!

!!!!!!!displacement!!!!!!!
FLST,2,1,1,ORDE,1
FITEM,2,36147
!*
/GO
D,P51X, ,0, , , ,UX,UY,UZ, , ,

!!rotation!!!!!!!
FLST,2,1,1,ORDE,1
FITEM,2,36147
!*
/GO
F,P51X,FX,0
FLST,2,1,1,ORDE,1
FITEM,2,36147
!*
/GO
F,P51X,FY,0
FLST,2,1,1,ORDE,1
FITEM,2,36147
!*
/GO
F,P51X,FZ,0

!!!!!!!symmetry!!!!!!!
FLST,5,4,5,ORDE,4
FITEM,5,7
FITEM,5,16
FITEM,5,-17
FITEM,5,63
ASEL,S, , ,P51X
NSLA,S,1
DSYM,SYMM,X, ,

!!!!!!!top surface!!!
FLST,5,3,5,ORDE,3
FITEM,5,13
FITEM,5,24
FITEM,5,29
ASEL,S, , ,P51X
NSLA,S,1
D,all,UY,0

!!!!!!!side!!!!!!!
FLST,5,3,5,ORDE,3
FITEM,5,10

```

FITEM,5,40
FITEM,5,64
ASEL,S,,P51X
NSLA,S,1
D,all,UY,0

```

```

!!!!!!!!!!!!!!solution set!!!!!!!!!!!!!!

```

```

/SOL

```

```

ANTYPE,static, new           !Specify analysis type,1-static
TUNIF,20,                    !Assing a uniform temperature at all nodes
TREF,20,                      !Define the reference temperature
SOLCONTROL,on                !Specifies whether to use optimized nonlinear
solution defaults and some enhanced internal solution algorithms
eqslv,SPARSE                  !Specifies the type of equation solver
KBC,0                          !Specifies ramped or stepped loading within a load step,
0 means rapped
ALLSEL,ALL
!
```

```

time, 1.3905
NSUBST,1
ldread, temp,,, 1.3905, , stress_uncouple, 'rth'
Solve
time, 8001.3905
NSUBST,1
ldread, temp,,, 8001.3905, , stress_uncouple, 'rth'
Solve

```