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ORIGINAL STUDY

Study The Effects of Temperature on Laser Cladding Process with Two Different Geometries Using COMSOL Multiphysics

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ABSTRACT

Due to the advancement of laser material processing and the high-demand of high-quality processing, COMSOL Multiphyiscs emerges as a powerful solution to the problem, offering multiple simulation in virtual environment with both 2D and 3D geometries. In this work, we aim to study the effects of thermal properties on the laser cladding using both 2D and 3D geometries with Nickle and Copper as promising candidates for rapid processing of materials. The work was done on a personal computer using commercially-available package of COMSOL Multiphysics 5.0. Results shows a notable increment of heat affected zone when the laser power increased. Additionally, the time parameter shows distinct and uniform distribution of the heat affected zone.

Keywords: Laser cladding, COMSOL Multiphysics, Thermal effects

1. Introduction

Laser cladding is a technique that allows for the deposition of thick protective coatings on low-cost substrates. The process can be described as an addition of one material by cladding on the surface of a substrate, where the heat source is a high-power laser beam [1]. As a cost-saving and efficient technique, laser cladding has extensive application on many fields, it attracts considerable attentions and has been intensively developed. Due to the rapid heating and cooling during laser cladding, the duration of molten pool is very short. Besides, the thermo-physical properties of material vary rapidly with the change of temperature, the phase transformation exists generally during the melting and solidifying. Therefore, it is difficult to measure the temperature distribution and observe the solidifying process of molten pool. In this case, the numerical simulation is necessary to be used in modeling temperature field, and it is capable of providing a complete thermal field analysis for laser cladding. In recent years, there have been some numerical simulations, especially finite element model (FEM), proposed to calculate the temperature field and research the cladding characteristics related to the thermal analysis [2]. Laser cladding, a versatile and innovative material deposition process, has gained significant attention in various industries due to its ability to enhance the surface properties of components, prolonging their service life and performance. This advanced manufacturing technique utilizes a high-power laser beam to selectively melt and fuse a powdered or wire feedstock onto a substrate, creating a durable and functional coating. At its core, laser cladding represents a fusion of cutting-edge laser technology and materials science, offering precise control over the composition, microstructure, and thickness of the clad layer. Unlike traditional welding processes, laser cladding minimizes the heat-affected zone, reducing the risk of distortion and maintaining the integrity of the substrate material. This makes it particularly well-suited for applications where intricate geometries or heat-sensitive materials are involved.

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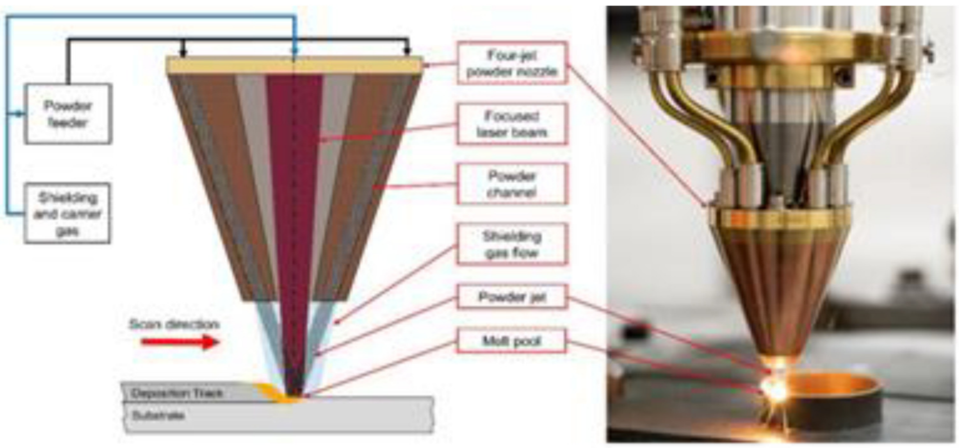


(a) (b)

Fig. 1. Laser cladding operation (a) Schematic (b) Real setup [3].

The process begins with meticulous substrate preparation, ensuring cleanliness and proper surface roughness to promote adhesion and bond strength. A suitable feedstock material, chosen based on the desired properties of the clad layer, is then deposited onto the substrate surface. This feedstock material can range from pure metals to complex alloys and composites, offering tailored solutions to a wide array of engineering challenges. During laser cladding, the high-energy laser beam is precisely focused onto the substrate, generating a localized molten pool at the interaction zone. The feedstock material, supplied either in powdered or wire form, is strategically introduced into this molten pool, where it rapidly melts and fuses with the substrate. As the laser beam traverses the substrate surface, successive layers of clad material are deposited, building up the desired coating thickness, as shown in Fig. 1.

The advantages of laser cladding are manifold. Its ability to achieve precise control over the clad layer thickness and composition allows for tailored solutions to specific application requirements. Moreover, the minimal heat input and rapid solidification inherent to the process result in minimal distortion and excellent metallurgical bond strength between the clad layer and the substrate. This, coupled with the versatility to deposit a wide range of materials, makes laser cladding indispensable in industries such as aerospace, automotive, oil and gas, and tooling. In conclusion, laser cladding stands at the forefront of advanced manufacturing technologies, offering unparalleled precision, efficiency, and versatility in enhancing the surface properties of engineering components. As industries continue to push the boundaries of performance and durability, laser cladding emerges as a transformative solution, driving innovation and excellence in material processing and surface engineering.

Laser cladding has various applications in different industries: Laser cladding is used for coating gas turbine engines, dies and drilling spindles, tools, and turbine blades to improve their wear and corrosion resistance [4]. It is also used to create a foam layer on Al-Si substrates, which can improve the tensile behavior of the material [5]. Laser cladding can produce uniform clad layers over 1 mm thick in a single pass, with low dilution by the substrate and high powder utilization efficiency, making it a competitive technique compared to continuous wave lasers [6]. Laser cladding can be used to coat engineering components with a variety of materials, including nickel-based alloys, to improve their wear and corrosion resistance [7]. The ABA cladding strategy, where additional weld seams are deposited between the initial weld seams, can be used to improve the quality and surface finish of laser cladding coatings [7]. Laser cladding finds diverse applications across various industries due to its ability to enhance the surface properties of components. Some notable applications of laser cladding include Wear and Corrosion Protection: Laser-clad coatings are extensively used to improve the wear resistance and corrosion resistance of components exposed to harsh operating conditions. Examples include hydraulic cylinders, pump shafts, valve seats, and oil and gas drilling equipment. Tool and Die Repair Laser cladding is employed for the repair and refurbishment of worn or damaged tooling components such as molds, dies, cutting tools, and punches. By selectively adding material to worn areas, laser cladding restores the geometry and extends the service life of these critical components. Aerospace Components In the aerospace industry, laser cladding is utilized for repairing turbine blades, compressor components, and aircraft engine parts. By selectively adding material to worn or damaged areas, laser cladding restores the dimensional accuracy and extends the operational lifespan of these high-value components.

Automotive Engineering: Laser cladding is employed in automotive manufacturing for applications such as reconditioning engine components, repairing worn transmission parts, and enhancing the wear resistance of critical components subjected to high loads and frictional forces.

Additive Manufacturing: Laser cladding is also used as a form of additive manufacturing, where complex three-dimensional parts are built up layer by layer using powdered feedstock material. This approach is particularly advantageous for producing customized or low-volume components with intricate geometries. Mold and Die Manufacturing: Laser cladding is utilized in the production of molds and dies for the plastics, metal forming, and die casting industries. By selectively adding wear-resistant materials to critical surfaces, laser cladding enhances the durability and longevity of molds and dies, reducing downtime and maintenance costs. Mining and Construction Equipment: Laser-clad coatings are applied to mining and construction equipment components such as excavator buckets, hydraulic cylinders, and wear plates to improve their resistance to abrasion, impact, and corrosion, thereby extending their service life in demanding operating environments. Medical Devices: Laser cladding is employed in the medical device industry for applications such as coating surgical instruments, dental implants, and orthopedic implants with biocompatible materials to enhance their wear resistance, corrosion resistance, and biocompatibility. These applications highlight the versatility and effectiveness of laser cladding in addressing a wide range of engineering challenges across various industries, ultimately contributing to improved component performance, longevity, and reliability

The FEM is a numerical technique used to solve complex engineering problems by discretizing the domain into smaller elements and applying mathematical equations to each element. Some key points about the finite element method based on the provided papers: The differential quadrature finite element method (DQFEM) is a combination of the differential quadrature method (DQM) and the standard FEM, which can simplify the construction of higher-order finite elements [8]. Aluminum-based composite materials, such as EN AC-43100 (AlSi10Mg(b) + SiC*/15p), can be used as an alternative to aluminum alloy for ship building to address the issue of fatigue failure due to cracking. Composite ship models using ANSYS software can be used to analyze the stress distribution and determine the safety of the design [9]. The penalty method in the finite element context can be used to solve elliptic problems in complicated domains by replacing the initial problem with a penalized one posed over a simply shaped domain that covers the original one. This method relies on two parameters, the space-discretization parameter (h) and the penalty parameter (ϵ), and a strategy to estimate the error in both parameters can be developed. The extended finite element method (X-FEM) is a methodology different from the classical finite element method, as it does not require the discontinuities to be in conformity with the mesh borders, allowing for the accurate solution of engineering problems in complex domains that may be impractical to solve using the classical finite element method [10]. The (FEM) is a numerical technique used for finding approximate solutions to boundary value problems for partial differential equations. It's extensively employed in engineering and applied mathematics for solving problems involving heat transfer, fluid dynamics, structural analysis, electromagnetism, and other physical phenomena.

Discretization: The first step involves dividing the problem domain into smaller, simpler subdomains called elements. These elements are usually geometrically simple shapes like triangles or quadrilaterals in 2D and tetrahedra or hexahedra in 3D. Approximation: Within each element, the behavior of the solution is approximated using interpolation functions, often referred to as shape functions. These functions approximate the behavior of the solution within each element based on known values at certain points called nodes.

Assembly The system of equations governing the problem is formulated by combining the contributions of each element. This involves assembling the element equations into a global system of equations that represents the entire problem domain. Solution The global system of equations is solved, typically using numerical techniques such as direct solvers or iterative methods. The solution provides values of the unknowns (e.g., displacements, temperatures) at the nodes Post-processing Once the solution is obtained, post-processing involves analyzing and visualizing the results to extract relevant information, such as stresses, strains, temperatures, or fluid flow patterns. FEM offers several advantages, including its ability to handle complex geometries and material properties, its flexibility in incorporating various boundary conditions, and its adaptability to parallel computing, allowing for efficient solution of large-scale problems. However, FEM also has limitations and challenges, such as the need for careful mesh generation, the potential for numerical instabilities, and the computational cost associated with solving large systems of equations, especially in three dimensions.

Laser cladding, a cutting-edge additive manufacturing technique, has emerged as a powerful method for enhancing the surface properties of engineering components. Leveraging the precision and versatility of laser technology, laser cladding offers a unique approach to depositing material layers onto substrates, imparting desirable properties such as wear resistance, corrosion protection, and thermal conductivity. In the realm of simulation-driven design and optimization, COMSOL Multiphysics stands at the forefront, offering engineers and researchers a comprehensive toolkit to explore and optimize the laser cladding process. At its essence, laser cladding involves the deposition of a molten material layer onto a substrate surface, typically achieved through the interaction between a high-energy laser beam and a feedstock material. The intricate interplay between thermal, fluid, and electromagnetic phenomena during the laser cladding process necessitates a multiphysics simulation approach for accurate prediction and optimization. COMSOL Multiphysics rises to the challenge, providing a versatile platform to simulate the coupled physics involved in laser cladding, including heat transfer, fluid flow, solid mechanics, and electromagnetic radiation. One of the key advantages of employing COMSOL Multiphysics for laser cladding simulations lies in its ability to capture the complex transient behavior of the process with high fidelity. Through the FEM framework, COMSOL facilitates the discretization of the simulation domain into finite elements, allowing for the numerical solution of partial differential equations governing the underlying physics. This enables engineers to investigate crucial aspects of the laser cladding process, such as temperature distribution, melt pool dynamics, material deposition, and residual stress formation, with unprecedented accuracy and detail.

Furthermore, COMSOL's extensive library of predefined physics interfaces and material properties provides users with a solid foundation to model various aspects of the laser cladding process. Whether simulating the interaction between the laser beam and the material surface, modeling powder delivery and distribution, or analyzing the thermal evolution of the workpiece-substrate system, COMSOL empowers users to tailor simulations to their specific requirements, facilitating in-depth exploration and optimization of laser cladding parameters. Moreover, COMSOL's multiphysics coupling capabilities enable engineers to capture the intricate feedback mechanisms between different physical phenomena inherent in the laser cladding process. By coupling heat transfer with fluid flow, for instance, engineers can investigate the influence of coolant flow rate on melt pool dynamics and solidification behavior. Similarly, coupling electromagnetic radiation with thermal analysis enables the study of laser-material interactions and their impact on material deposition efficiency and quality. In the pursuit of advancing laser cladding technology, simulation-driven approaches play a pivotal role in accelerating innovation and optimization. Through its seamless integration of multiphysics simulation capabilities, COMSOL Multiphysics empowers engineers and researchers to unlock the full potential of laser cladding, enabling the design of high-performance engineered surfaces with enhanced functionality and durability. Here we focus on the simulation of 2D and 3D geometries and demonstrate the cladding operation using metal materials (nickel and copper) with their theoretical models. The work is organized by stating the materials and methods with material properties and necessary equations then the simulation operation with figures showing the 2D and 3D images of the work including the meshing operation. And finally the results after implementation are shown in results and discussion section.

2. Materials and methods

Although there is no doubt about the tremendous industrial potential of metal additive manufacturing techniques such as laser metal deposition, the technology still has some intrinsic quality challenges to overcome before reaching its industrial maturity. Noncontact in situ monitoring of the temperature evolution of the workpiece could provide the necessary information to implement an automated closed-loop process control system and optimize the manufacturing process, providing a robust solution to these issues. However, measuring absolute temperatures is not self-evident: wavelength-dependent emissivity values vary between solid, liquid, and mushy metallic regions, requiring spectral information and dedicated postprocessing to relate the amount of emitted infrared radiation to the material temperature [11, 12]. The thermal effects in laser cladding can be described by the following equation: $T = f(P, v, d, k, \rho, c)$ Where: T is the temperature distribution, P is the laser power, v is the scanning speed, d is the laser beam diameter, k is the thermal conductivity of the material, ρ is the density of the material, and c is the specific heat capacity of the material. The temperature distribution can be analyzed using heat transfer equations and numerical finite-element methods. Laser cladding parameters such as laser power, scanning speed, and spot diameter can affect the depth of the heat-affected zone and the residual stress distribution in the cladding layer.

In the process of the laser cladding, the cladding track not only absorbs laser energy, but also carries out thermal conduction, radiation and convection, resulting in partial energy loss. The energy transfer in the cladding track can be expressed as

$$Q(x, y, t) = \left(\frac{2p \cdot \eta_1}{\pi \cdot r^2} \exp\left\{ -\frac{2(x - V_S \cdot t)^2 + (y)^2}{r^2} \right\} - K\frac{\Delta T}{\Delta n} - h(T - T_f) - \sigma_b \varepsilon (T^4 - T_f^4) \right) \tag{1}$$

Where:

p: is the laser power

η_1: is the absorption rate of laser energy

r: is the radius of the laser beam,

V_S: is the scan speed

t: is the time of laser irradiation

x and y: are the coordinate systems where the laser spot is located,

K: is the thermal conductivity coefficient

ΔT: is the temperature variation,

Δn: is the direction of heat transfer (x, y, z), h is the heat transfer coefficient of the convective,

T_f: is the ambient temperature

σ: is the Stefan–Boltzmann constant

ε: is the emissivity

The energy absorbed by the powder is equal to the change of its internal energy, and the mass of the powder is set as M. Then the heat Q1 absorbed by the powder, from the ambient temperature to melting, and then to the instantaneous temperature T, can be expressed as

$$Q_1 = C_\rho \cdot M \cdot \Delta T + M \cdot \Delta H_f \tag{2}$$

Where:

C_ρ: is the heat capacity of the powder material

ΔH_f: is the latent heat

The energy produced by laser on powder material can be expressed as

$$Q_2 = \rho \cdot t \cdot \eta \tag{3}$$

where η is the absorption efficiency of the laser energy by the powder.

According to the conservation of energy

$$M = \frac{\rho \cdot t \cdot \eta}{C_\rho \cdot \Delta T + \Delta H_f} \tag{4}$$

Table 1. Copper properties.

Property	Symbol	Value and Unit
Thermal conductivity	K	401 W/(m·K)
Coefficient of thermal expansion	Alpha	16.6×10^{-6}/°C
Heat capacity at constant pressure	Cp	0.385 J/(g·K)
Density	Rho	8.96 g/cm^3
Young's modulus	E	110–130 GPa
Poissons' ratio	Nu	0.30–0.36

Table 2. Nickel properties.

Property	Symbol	Value and Unit
Thermal conductivity	K	90.9 W/(m·K)
Coefficient of thermal expansion	Alpha	13.3×10^{-6}/°C
Heat capacity at constant pressure	Cp	0.444 J/(g·K)
Density	Rho	8.91 g/cm^3
Young's modulus	E	190–210 GPa
Poissons' ratio	Nu	0.30 to 0.34

Table 3. 2D geometry mesh properties.

Element	Value
Maximum element size	0.325
Minimum element size	0.015
Curvature factor	0.6
Maximum element growth rate	1.5
Predefined size	Coarser
Maximum element growth rate	1.5
Predefined size	Coarser

Table 4. 3D Geometry properties.

Property	Value
Space dimension	3
Number of domains	9
Number of boundaries	60
Number of edges	121
Number of vertices	72

The density of the powder material is ρ_P, Then the cross-sectional area of the cladding track is

$$S = \frac{\rho \cdot t}{\rho_P \cdot V_S \cdot (C_\rho \cdot \Delta T + \Delta H_f)} \tag{5}$$

The properties of copper and nickel materials are listed in Tables 1 and 2, respectively.

3. Results and discussion

The geometry of the 2D work is defined as three layers of Nickle, and Copper respectively, Fig. 2 below is the view of geometry and the properties used in the software, while Table 3 shows the 2D geometry mesh properties.

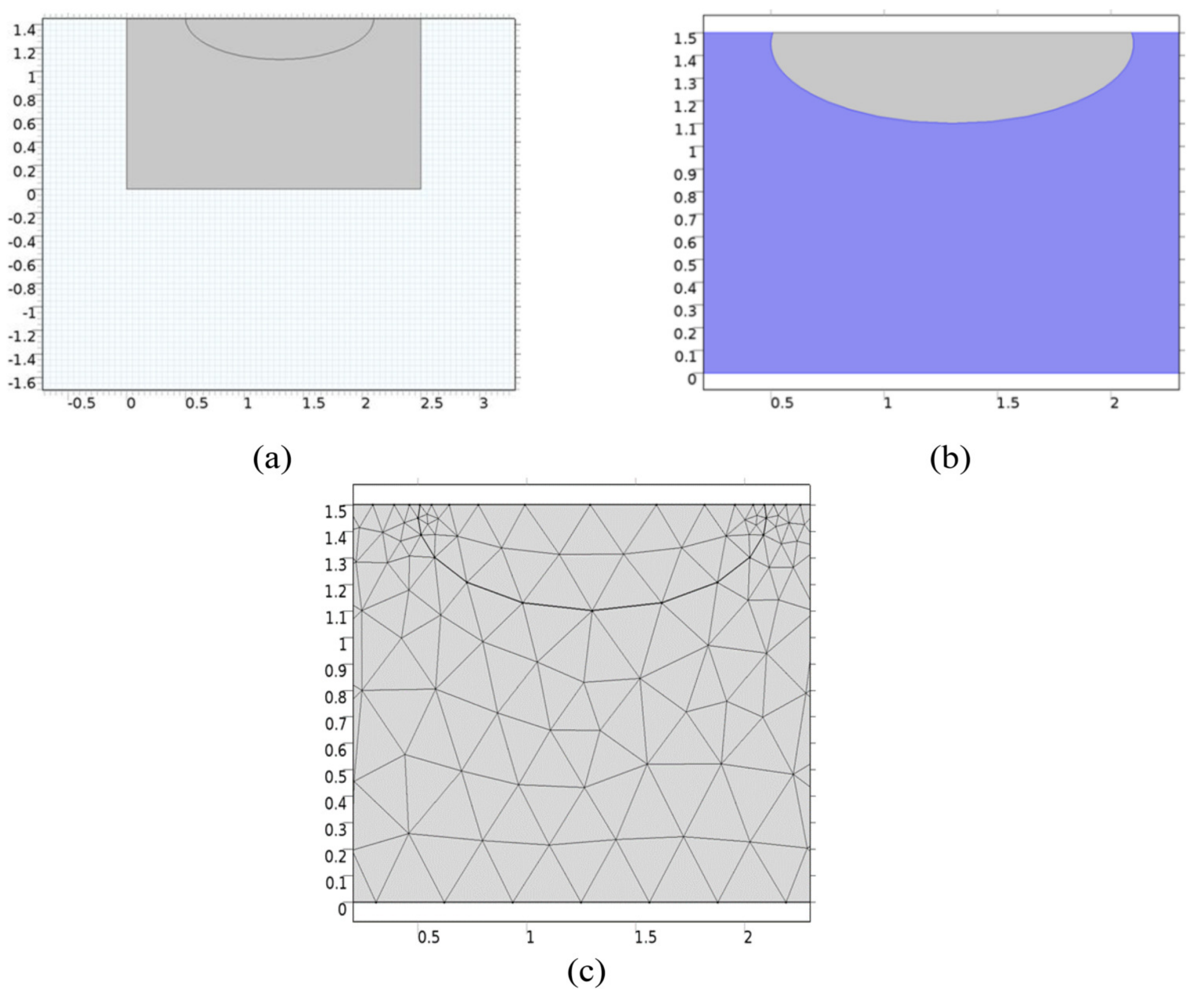


Fig. 2. 2D geometry of the work (a) geometry view (b) material view (c) mesh view.

Table 5. Material properties.

Property	Value	Unit
Coefficient of thermal expansion	17e-6[1/K]	1/K
Heat capacity at constant pressure	385[J/(kg*K)]	J/(kg*K)
Density	8700[kg/m^3]	kg/m^3
Thermal conductivity	400[W/(m*K)]	W/(m*K)
Young's modulus	110e9[Pa]	Pa
Poisson's ratio	0.35	1

The geometry of the 3D work is defined as three layers of Nickle, Copper and Air respectively, Fig. 3 below is the view of geometry and the properties used in the software, while Table 4 shows the 3D geometry mesh properties.

The material's properties used in the work are described in Tables 3 and 4 while the Table 5 below shows the copper properties in the COMSOL Multiphyiscs.

Heat Transfer equations used in the COMSOL Multiphysics can be summarized as the equations below

$$\rho C_P \mu \cdot \nabla T = \nabla \cdot (k \nabla T) + Q \tag{6}$$

$$-n \cdot (-k \nabla T) = o \tag{7}$$

$$\rho C_P \mu \cdot \nabla T = \nabla \cdot (k \nabla T) + Q + Q_{vd} + Q_p \tag{8}$$

$$-n_{dst} \cdot (k \nabla T)_{dst} = n_{src} \cdot (k \nabla T)_{src} \tag{9}$$

$$T_{dst} = T_{src} \tag{10}$$

The Application of mesh has been done using size mesh and tetrahedral meshing operation, the mesh outlines and properties are shown in Table 6 below.

As the Laser is considered as a heat source in the thermal simulation and the process is laser cladding using both Nickle and copper material in two different geometries one with 2D and the other with 3D geometry the results shows that when the laser

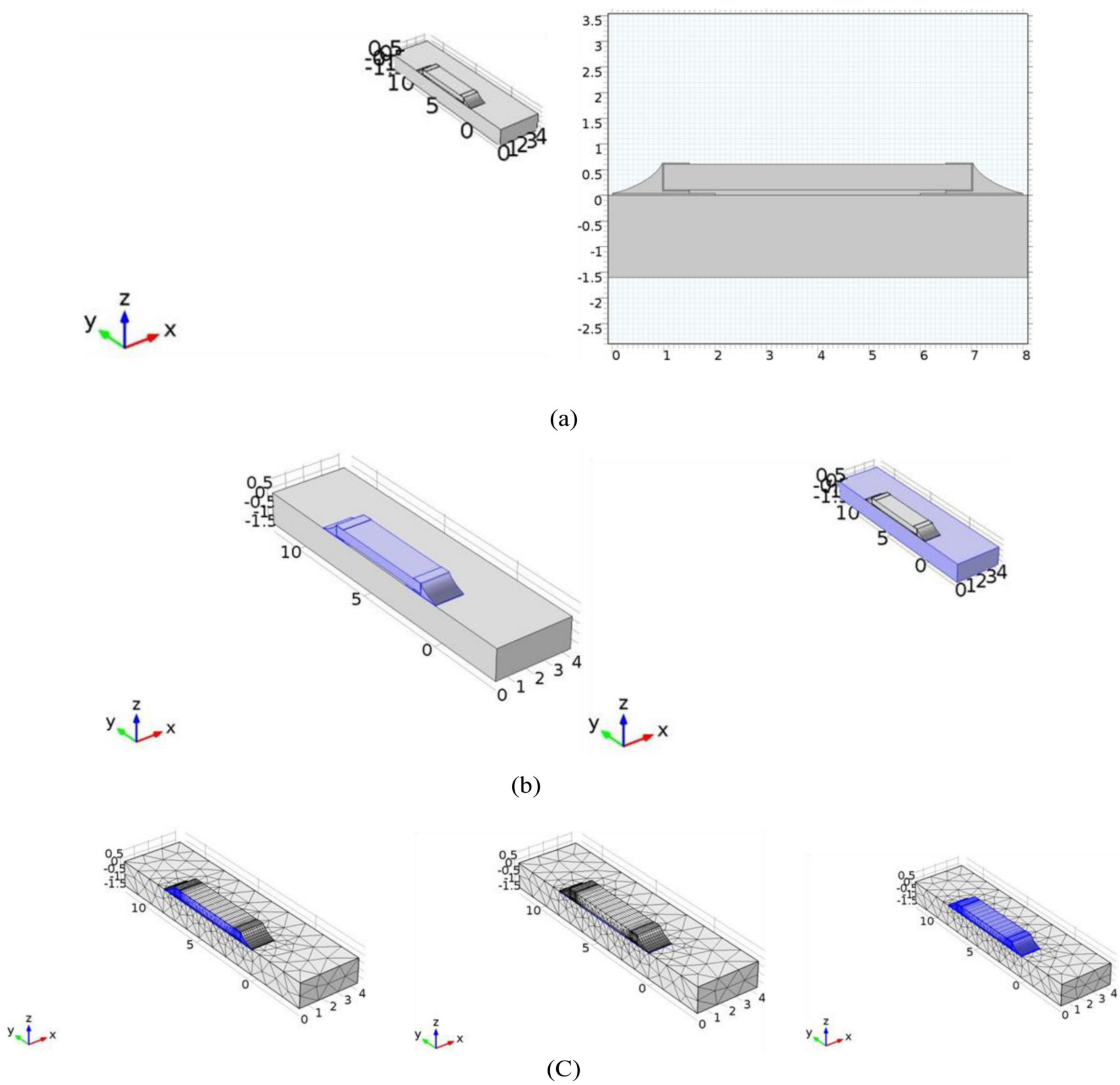


Fig. 3. (a) 3D Geometry of the work, (b) Material's choice to the 3D geometry (c) Mesh choice to the 3D geometry.

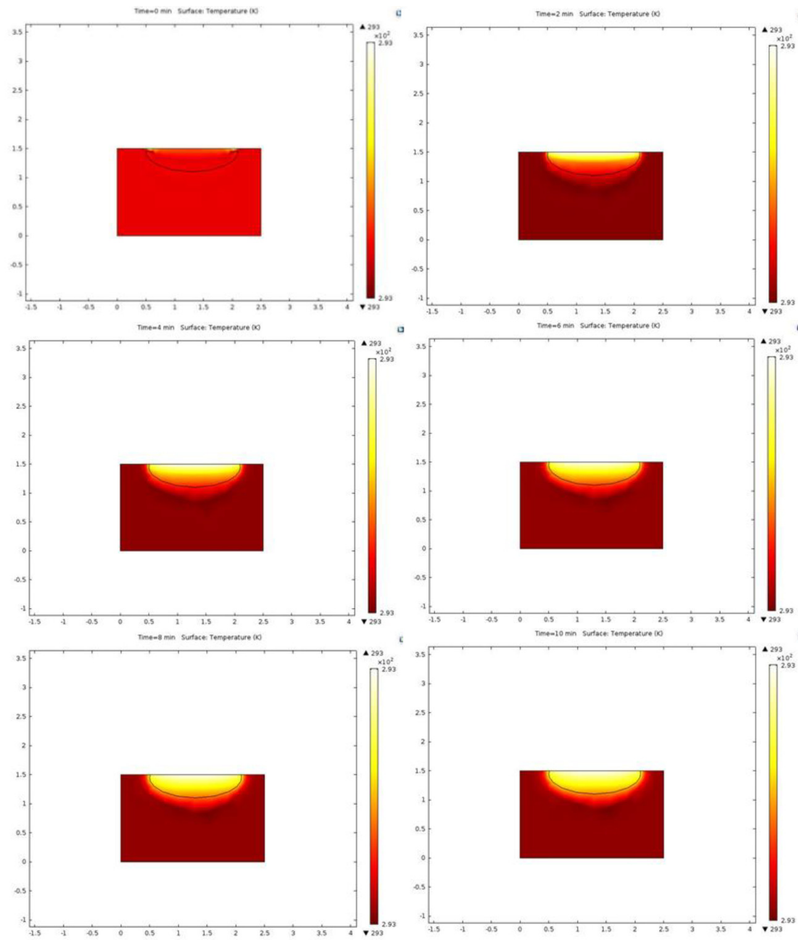
power is increased leads to the increase of the temperature on the materials in both geometries. Also, when the time passes by the heat distribution changes from being concentrated to the edge points to form a uniform heat affected zone (HAZ). The above discussion is supported by the data in Fig. 4(a), Fig. 4(b) and Fig. 4(c). Although this is theoretical simulation, in practice, researchers can select the required laser power to demonstrate the cladding and the temperature according to the properties of the materials used. Researchers can work on different materials and different geometries in simulation and in practice as future work.

Table 6. Mesh properties to the 3D geometry.

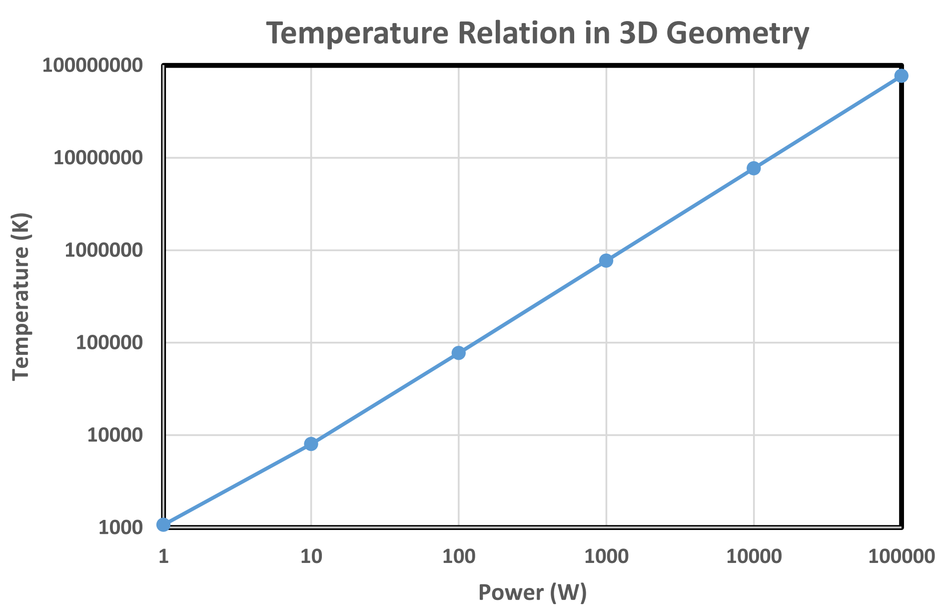
Property	Value
Maximum element size	1.28
Curvature factor	0.5
Resolution of narrow regions	0.6
Maximum element growth rate	1.45
Predefined size	Fine
Custom element size	Custom

4. Conclusion

The heat affected zone is uniform across the materials. As laser power increase the temperature increases. As time pass by the heat affected zone shows uniformity in the distribution



(a) (b)



(c)

Fig. 4. (a) Heat distribution in 2D geometry by changing the time of applying the laser source (b) Heat distribution in 3D geometry by changing the input laser power (c) Temperature relation in different laser powers.

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