FINITE ELEMENT MODEL FOR LASER WELDING OF TITANIUM

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Abstract

This paper presents a finite element numerical analysis of the heat transfer in the laser welding process of Ti6Al4V titanium alloy. For sake of validation, 1.5 mm thick butt joints were made using a fiber laser. The finite element calculation of the process was carried out by a parametric design language (APDL) available in the ANSYS finite element code. The numerical modeling was conducted focusing the attention on the model of the laser-material interaction, which allowed to predict the temperature distribution during the thermal cycle and the related phase transformations. The parametric solution was implemented in order to make it suitable for different welding conditions. The numerical model was calibrated both by comparison between the weld transverse cross section of and the thermal cycles detected by thermocouples during welding. Then the simulation was conducted and the evolution of the temperature distribution during the process was calculated. The comparison between experimental and numerical results stressed the evidence of the suitability of the here-presented model for the simulation of the laser welding process of titanium alloys.

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Selection and peer-review under responsibility of the International Scientific Committee of “9th CIRP ICME Conference”

Keywords: laser welding, titanium, modeling, numerical analysis

1. INTRODUCTION

Titanium and titanium alloys are widely used in many sectors like aerospace, chemical, medical and energy industries. This is due to several unarguable properties such as excellent corrosion resistance, bio-compatibility, good temperature performance and high specific mechanical resistance that made these alloys almost irreplaceable in many applications (1-4). Joining processes play a fundamental role in the productive scope of many industries and many welding techniques have been studied and developed to process these alloys. Among all laser beam welding is strongly used because of its versatility, small focus spot diameter, high specific heat input, optimal performance and good reliability (5). Many works have been conducted on experimental analyses of laser welding process adopted to produce titanium and titanium alloys welds. For example Xiao-Long Gao et al. (6) studied the correlation between the welding process parameters and the porosity formation. E. Akman et al. (7) analyzed microstructure and tensile strength of titanium joints performed through a laser beam source. They focused their attention on the correlation between the depth of penetration and the ratio between pulse energy and pulse duration. While P.E. Denney and E.A. Metzobower (8) assessed the influence of different preparation procedures. Other works concern the experimental analysis of other conventional or hybrid welding technique used to perform titanium alloys joints (9-12). Several works treated also the comparison between different conventional and hybrid welding techniques in term of mechanical, microstructural and aesthetical quality (13, 14). In the last decades, in order to increase and optimize the efficiency in manufacturing, many models of the welding processes have been developed and implemented in the industries and in the academic world. Connections between theoretical aspects and production as well as the development of quantitative solutions can be carried out by implementing numerical models (15). During the welding process, because of the heat input transferred to the material, heat transmission inside the workpiece and heat exchange with the external environment occur (16). Numerical simulation of heat manufacturing processes is preferred to analytical methods for modelling in welding technology. In fact as the laser beam interacts with the surface...
of the work-piece during its passage, very rapid series of heating and cooling cycles are achieved. Therefore it results to be difficult to adopt analytical model technique to investigate about the process. Instead numerical models are suitable to assess the thermal cycles and their relationship with process parameters.

FEM simulations are nowadays useful to predict the weld pool shape for various combinations of process parameters from the temperature distribution plots. Many numerical studies have been conducted in previous researches and various aspects have been investigated. For example several authors developed numerical models to predict the weld bead geometry in laser spot welding of AISI 304 providing the shape of beads for different process parameters and comparing experimental and numerical results (17, 18). Bappa Acherjee et al. (19) conducted a numerical analysis to simulate laser welding of different materials and predict the transient temperature field and the weld dimensions. Mohammad Akbari et al. (20) investigated about a numerical simulation to model temperature distribution and predict the geometry of various zones of titanium joints performed with a laser beam source.

Temperature and flow fields during full penetration laser beam welding were simulated by Hanbin Du et al. (21). The simulation of EBW of different grade titanium was conducted by Konrad Adamus et al. (22).

Also solid-state welding processes were numerically simulated in previous researches. For example, many authors treated the numerical simulation of FSW process of titanium alloys (23-25).

In this work the simulation of the thermal phenomenon during the laser beam welding process of Ti6Al4V titanium butt joint is presented. The thermal analysis is concentrated on the prediction of the heat transfer in the weld. A distributed volume heat-source was validated on the basis of the comparison with the experimental specimen cross section and temperature measurements by thermocouple. The temperature distribution in the overall weldment and the shape and size of the fusion zone, heat affected zone and geometry of the molten pool were predicted.

Two welding condition were considered since they generated different fused zone geometry. The thermal source was modified for accommodate both conditions. Numerical and experimental results were compared to evaluate the quality of the implemented model.

2. Numerical procedure

2.1 Material properties

In this work Ti6Al4V titanium alloy butt weld with a thickness of 1.5 (mm) were assessed. A 3D finite element model was developed to simulate the thermal phenomenon during welding. A commercial FEM code Ansys was used. Table 1 shows the chemical composition of the alloy considered.

| Tab. 1: Chemical composition of Ti6Al4V Titanium alloy | C  | Fe  | N2  | O2  | Al  | V  | H2  | Ti  |
|------------------------------------------------------|----|-----|-----|-----|-----|----|-----|-----|
| TRASHV                                               | <0.08 | <0.25 | <0.05 | <0.2 | 5.5 | 3.5 | <0.0375 | balance |

Thermo-physical properties of the material were assumed to be isotropic and temperature-dependent according to the record in the literature.

2.2 Experimental tests

An Ytterbium Laser System (IPG YLS-4000), with a maximum power output available equal to 4 kW was used. The laser source was delivered via a 200 µm diameter fiber, with a beam parameter product (BPP) equal to 3.1 mm*mrad.

The laser beam, whose wavelength was 1070.6 nm, was focused by a lens with a focal distance equal to 250 mm) producing a spot diameter of 0.4 mm on the surface of the work-piece. Argon was chosen as shielding gas.

During the experimental analysis two different combinations of process parameters were adopted to perform the welds. Table 2 shows the process parameters.

| Tab. 2: Process parameters adopted to carry out the experimental analysis |
|---------------------------------------------------------------|
| Case | Laser power (W) | Welding speed (mm/min) | Focus diameter (µm) |
|------|-----------------|------------------------|---------------------|
| 1    | 1500            | 3500                   | 300                 |
| 2    | 1500            | 2500                   | 300                 |

The specific heat input adopted to perform sample 1 is largely different from that used to perform sample 2 and a different bead shape of the cross section was obtained. So in this paper two different cases are discussed.

The first is that in which the bead had a truncated cone-shaped, which was obtained with low specific heat input (figure 1). The second is that in which the bead had an hourglass-shaped bead, which was obtained with high specific heat input (figure 2).

The calibration of the numerical models concerning the two cases has been conducted in two different ways in order to show the goodness of both the methods. Therefore the model was calibrated by comparing the cross section of the experimental specimens with the numerical ones. For case 2 the validation was carried out by acquiring the actual temperatures by a thermocouple recording system.

![Case 1](image1.png)

Fig. 1. Cross section of a typical truncated cone-shaped welding bead

![Case 2](image2.png)

Fig. 2. Cross section of a typical hourglass-shaped welding bead

2.3 Definition of geometry and meshing

The geometry of the sheets adopted to perform the numerical assessment for both the cases are shown in figures 3 and 4.
Figure 4 shows also the location of the thermocouples. Because of the different ways adopted to calibrate the models different geometries of the sheets were realized.

In fact the calibration through the comparison of thermal cycles requires a fine mesh since the thermocouples were positioned close to the welding line along the entire weld on the surface of the sheet. Therefore as regards case 1 the dimensions were 20x10x1.5 (mm), while for the case two were 100x50x1.5 (mm).

The type of element chosen to carry out the thermal analysis is an eight nodes quadratic three dimensional solid elements SOLID 70. Several convergence tests were conducted to find a suitable number of elements for the model of the plate. Figure 5 shows the results of the meshing procedure. Eight elements in the direction along the thickness were evaluated to be the optimal solution.

A fine mesh was adopted in the region close to the welding line. Therefore the dimensions of the elements in the horizontal plane were varied from 0.05x0.05 (mm) (in the region nearest to the welding line) to 0.05x0.22 (mm) (in the adjacent region). Finally at a certain distance from the welding line, where the effects of the laser source can be considered to be negligible. Therefore, the mesh size was progressively reduced by a factor of three.

2.4 Boundary conditions

Convective load of the upper and lateral surfaces was assumed equal to 20 (W/m²K). The conductive thermal exchange between the sheets and the support system was introduced through a convective coefficient of 200 (W/m²K) for the bottom surface.

Moreover the region closed to the welding line was not subjected to the thermal convective exchange because of the presence of the laser beam.

The environmental temperature at the starting condition and the initial temperature of the sheets were assumed to be equal to 20 (°C).

The irradiation phenomenon was neglected.

2.5 Modeling of the heat source

A stationary process of laser welding was considered. The conservation of energy was described by the thermal flux, specific heat and a distributed volume heat-source in differential equations (26).

The model of the heat source was based on the thermal load and the subsequent heat conduction through several specific elements next to the welding line.

At first the nodes were selected in a spherical local system reproducing the truncated cone shape of the bead (as concerns case 1) or through two opposite spherical local systems (as concerns case 2, hourglass shape).

As shown in figures 6 and 7, the selection depends on the laser beam spot diameter and the welding speed.
The heat load, defined by the equation 1, was introduced into the elements.

\[ H_{\text{gen}} = \frac{P}{V} \quad (1) \]

where \( P \) is the total power transmitted by the laser beam source and \( V \) is the volume, whose shape depends on the global heat input.

The heat source model was calibrated through the macrographs detected from the cross section of a specimen realized experimentally. In case 2 the calculated temperatures were compared with those detected during the welding cycle by thermocouples, whose layout is shown in Fig. 4.

2.6 Modeling of time evolution

The movement of thermal load was simulated in order to achieve the nodal temperature history in function of time. The thermal load distribution was computed at the beginning of each cycle of the loop.

So when the load moves from the previous to the consequent load step the former load step is deleted. The heat loads are imposed by small increments by using a DO loop command. The time step required for a specific welding speed was determined by dividing the distance between two consecutive elements sets with the beam speed.

Therefore a continuously moving of the laser beam with a specific welding speed and a certain thermal load was simulated with good accuracy.

3. Calibration of the numerical model

The calculation was performed with a personal computer. Equation 1 defines the internal thermal load imposed to simulate the heat source during the key-hole laser beam process.

Energy losses involved in the process are due to the reflectivity of the material, the loss of power in the machine, the interactions between laser beam and shielding gases.

Therefore, the power transmitted to the material and converted to heat results to be lower than that produced by the emission material of the laser. Therefore, in order to compute these causes of power loss, a calibration factor \( K \) was introduced:

\[ K = \frac{P_{\text{eff}}}{P} \quad (2) \]

where \( P_{\text{eff}} \) is the effective power transmitted to the material and \( P \) is the ideal power produced by the laser without considering loss elements.

As described in details previously, two cases were analyzed and two different ways were adopted to calibrate the models.

The thermal source was validated by comparing the cross section of the specimen performed experimentally with the temperature distribution in the same section.

Coefficients of calibration \( k \) for both the truncated cone shape bead (case 1, Fig. 8) and hourglass shape bead (case 2, Fig. 9) were determined and they resulted to be 0.22 and 0.15 respectively.

After the correction of the internal thermal load considering the loss contribute, numerical data approached experimental results with good approximation (as shown in figures 8 and 9).

In particular, in figure 8 the cross section of the specimen is compared with the temperature distribution achieved with the numerical analysis.

In the FZ the material reached temperatures higher than 1650 (°C) that is the fusion temperature of the alloy adopted, while in the HAZ temperatures between 1000 (°C) and 400 (°C) were obtained. The model that simulates the case 2 was calibrated comparing the thermal cycles achieved experimentally through thermo-couples with those achieved numerically.

![Fig. 8. Calibration of the numerical model by comparing the cross section of the specimen and the cross section achieved through the numerical analysis (case 1).](image1)

![Fig. 9. Calibration of the numerical model by comparing the cross section of the specimen and the cross section achieved through the numerical analysis (case 2).](image2)

As shown in Fig. 10 the maximum value of temperature reached was about 500 (°C). It was outside the heat affected zone as it was confirmed by the macrography of the weld.

![Fig.10. Calibration of the numerical model by comparing the thermal cycles of case 2](image3)
In fact, as presented in figure 4, the thermo-couples were positioned at 1.5 (mm) distant from the welding line while the base metal origin was around 1 mm from the weld centerline. It can be observed that the thermal cycle detected with the thermocouple approached that obtained numerically with a very good agreement.

4. Results and discussion

Figures 11 and 12 show the temperatures in the cross section of the welding bead for a fixed load step and for both the heat source volumes. As concerns figure 11, the highest values of the temperature were achieved at the top surface the welding line. The values of temperatures achieved are higher than 5000 (°C). Therefore vaporization phenomena of the material should be considered to simulate the interaction between laser beam and material with greater accuracy.

In figure 12 it can be observed that, because of the difference in the convective thermal exchange between the upper surface and the bottom surface, the temperatures distribution presented a double cone shape.

The temperature distribution at the upper surface and in the longitudinal plan along the welding line at 1.07 (s) after the beginning of the process for case 2 are shown in figures 13 and 14, respectively. The iso-thermal curves assumed an elliptical geometry caused by the movement of the thermal source that moves passing on zones heated by the thermal load in the previous step. Figure 13 shows that the hourglass shape was produced also in the longitudinal plan. This is due to the selection of the nodes in the phase of introduction of the thermal load that was carried out in 3D spherical local systems and not in a 2D system.

5. Conclusions

In this work the numerical analysis of the laser welding process of 1.5 mm thick Ti6Al4V titanium alloy butt weld was presented. Both experimental test and finite element simulation of the process were carried out in order to achieve a predictive model for the temperature distribution during the laser welding thermal cycle.

The following outputs worth to be underlined.

- The choice of modelling the heat source by selecting the nodes and applying a heat generation load was effective and enough accurate. This method approximated the
welding key-hole behavior. Different welding conditions were simulated by modifying the volume subjected to the nodal thermal load

- Two different ways to calibrate the model were used. Both the calibration through the thermal cycle registered by a thermocouple system and the calibration through comparison with the cross section of the specimen produced experimentally prove the model validity.

- A calibration factor was necessary for both the truncated cone shape bead and the hourglass shape fused zone. They resulted to be equal to 0.22 and 0.15 respectively.

- Eventually, the temperature distribution was calculated for different welding conditions. Numerical results approached experimental data with good accuracy.

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