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Laser Welding of Titanium Alloy Ti64 to Polyamide 6.6: Effects of Welding Parameters on Temperature Profile Evolution

A. Al-Sayyad, P. Lama, J. Bardon, P. Hirchenhahn, L. Houssiau, P. Plapper

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***Abstract*—**Composite metal–polymer materials, in particular titanium alloy (Ti-6Al-4V) to polyamide (PA6.6), fabricated by laser joining, have gained cogent interest among industries and researchers concerned with aerospace and biomedical applications. This work adopts infrared (IR) thermography technique to investigate effects of laser parameters used in the welding process on the three-dimensional temperature profile at the rear-side of titanium, at the region to be welded with polyamide. Cross sectional analysis of welded joints showed correlations between the morphology of titanium and polyamide at the weld zone with the corresponding temperature profile. In particular, spatial temperature profile was found to be correlated with the laser beam energy density, titanium molten pool width and depth, and polyamide heat affected zone depth.

***Keywords*—**Laser welding, metals to polymers joining, process monitoring, temperature profile, thermography.

I. INTRODUCTION

METAL–polymer assemblies have gained interest among industries and researchers due to their hybrid properties combining the low cost, low density, and high deformability of polymers with high strength to toughness ratio of metals, thereby creating products with tailored properties. Ti-6Al-4V and PA6.6 are both biocompatible and used in a wide variety of products including pacemakers, dental implants, and denture components [1]-[4]. Current metal–polymer joining methods include adhesive bonding, press fitting, and mechanical fastening. However, those methods involve either hazardous chemicals or geometrical constraints. On the other hand, a welding process like laser joining is an easily automated rapid process that can produce miniaturized joints with high design flexibility. Success of the laser welding process depends on the careful consideration of the joining parameters to ensure melting of the polymer while preventing its degradation [5]. This raises the importance of analyzing the temperature at the interface of the metal–polymer partners during the welding process.

Several process monitoring techniques, such as pyrometers and IR photodiodes and cameras, have been used to determine temperature at the weld zone during laser welding processes. However, those methods are generally used to monitor the keyhole generated on the metal rather than the interface temperature between joining partners [6]. In the case of metal–polymer laser welding, researchers [7], [8] used thermocouples to monitor the interface temperature during the welding process. However, this method does not provide sufficient information regarding the temperature spatial distribution. Lamberti et al. [9] developed a technique using an IR camera to analyze the temperature profile at the rear-side of aluminum utilizing the laser parameters used during joining with polyamide. However, the effects of tuning laser parameters values on the temperature profile were not reported. Concerning laser joining of Ti-6Al-4V–PA6.6, Al-Sayyad et al. [5] investigated the effects of joining parameters on the joint strength and quality, reporting a decline in joint strength along with an increase of weld defects as a result of increasing the laser energy density. In this research, the effects of laser welding parameters on the rear-side temperature of Ti-6Al-4V at the area to be welded with PA6.6 is investigated using IR thermography techniques and correlated with energy density, and morphology of joining partners.

II. METHODOLOGY

A. Materials

For these experiments, 0.5 mm thick titanium (Ti-6Al-4V) with geometry of 30 mm × 60 mm was used for welding with 4 mm thick polyamide (PA6.6) with geometry of 25 mm × 70 mm. Ti-6Al-4V is an alpha–beta alloy that roughly contains 6% Aluminum (alpha-stabilizing) and 4% vanadium (beta-stabilizing) alloying elements by weight. Samples were wiped with ethanol at room temperature prior to the welding process to clean their surfaces.

B. Laser Welding

Laser welding was performed using fiber laser (TruFiber 400 from TRUMPF) with a wavelength of 1070 nm and a spot size of 31 μm. During the welding process, samples were clamped in an overlap configuration as shown in Fig. 1, and the laser beam was focused and irradiated on the surface of

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Adham Al-Sayyad is with University of Luxembourg, 6 rue Coudenhove-Kalergi, L-1359 Luxembourg (corresponding author, phone: +352-466644-6034; fax: +352-466644-36034; e-mail: adham.alsayyad@uni.lu).

Prashant Lama was with University of Luxembourg, 6 rue Coudenhove-Kalergi, L-1359 Luxembourg (e-mail: Prashant.lama.001@student.uni.lu).

Julien Bardon is with Luxembourg Institute of Science and Technology, 5 avenue des Hauts-Fourneaux, L-4362 Esch-sur-Alzette, Luxembourg (e-mail: julien.bardon@list.lu).

Pierre Hirchenhahn andLaurent Houssiau are with Université de Namur, 61 Rue de Bruxelles, 5000 NAMUR, Belgium (e-mail: pierre.hirchenhahn@unamur.be, laurent.houssiau@unamur.be).

Peter Plapper is with University of Luxembourg, 6 rue Coudenhove-Kalergi, L-1359 Luxembourg (e-mail: peter.plapper@uni.lu).

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titanium. Part of the laser beam's energy was absorbed and transferred to the interface in the form of heat energy causing polyamide to melt and adhere to titanium during solidification, thus creating a joint. The laser beam followed a spiral trajectory shown in Fig. 1, and argon shielding gas was used to prevent titanium from oxidation and reacting with the atmosphere. Laser welding parameters were kept constant during the investigations, except for the laser welding power and beam guidance speed (V), as shown in Table I, to study their effects on the morphology of the joining partners and the corresponding temperature profile.

TABLE I
INVESTIGATED PARAMETERS

Parameter	Power (W)	Beam Guidance Speed (mm/s)	Energy Density (J/mm^2)
1	60	900	2.7
2	60	700	3.5
3	80	900	3.7
4	120	900	5.5

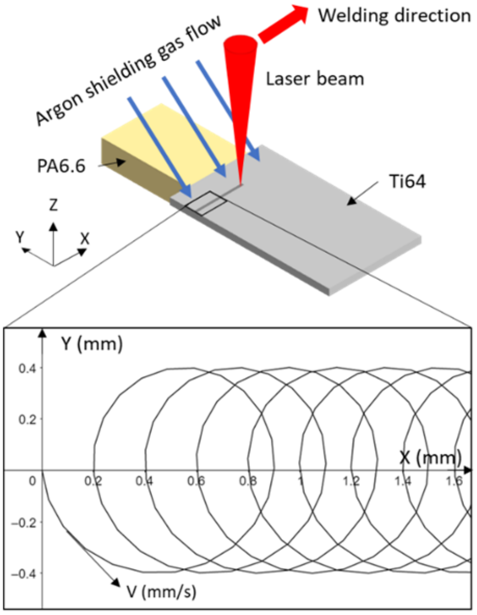

Fig. 1 Laser welding setup

C. Cross Sectional Analysis

Cross sectional analysis of the welded joints was performed in order to study the effects of joining parameters on titanium microstructure and polyamide morphology. Samples were cut perpendicularly to the weld path, and embedded in a cold mounting epoxy resin (epofix from Struers) to avoid any thermal effect of hot mounting on the polyamide's morphology. Then, mounted samples were grinded and finely polished. Afterwards, samples were etched by submerging in Kroll's reagent (92 ml H_2O, 6 ml HNO_3, 2 ml HF) for 30 seconds before rinsing with distilled water. Cross sections were observed using a Leica DM4000 M microscope. Polyamide morphology was investigated using polarized light microscopy.

D. Thermography

IR thermography imaging was performed as shown in Fig. 2 using VarioCAM, IR camera from InfraTec with a spectral range of 8-13 µm to investigate the effects of welding parameters on the interface temperature. Considering the optical opacity of polyamide to the IR frequencies range, titanium samples were placed freely i.e., without their joining partner, to be able to detect the rear-side temperature profile on titanium. Therefore, it is expected that the measured peak temperature at the rear-side of free titanium is different from the actual interface peak temperature of the assembly during the welding process. Rear-side (facing the IR camera) of titanium was coated with high emissivity black paint (Crown 7221), which can withstand temperatures up to 649 °C to insure a high emissivity. The temperature calculations were performed assuming an emissivity value of one. A shooting frequency of 30 Hz, capturing 30 frames per second, was utilized while keeping a constant number of frames across all samples to avoid temporal bias. The analysis was performed across a length-defined line, located at the center of the thermography frame and perpendicular to the feed speed, to avoid any spatial bias. Germanium glass filter of 5 mm thickness, transmitting wavelengths from 2 µm to 14 µm, was used to protect the IR camera from possible damages caused by reflected laser beam radiations. Concave mirror from Edmund optics, with a protective gold coating working in a wavelength range of 0.7 µm to 12 µm, was used to reflect the generated IR radiations and guide it to the IR camera. Plastic slab was placed below the laser path to absorb the laser beam in case of breakthrough.

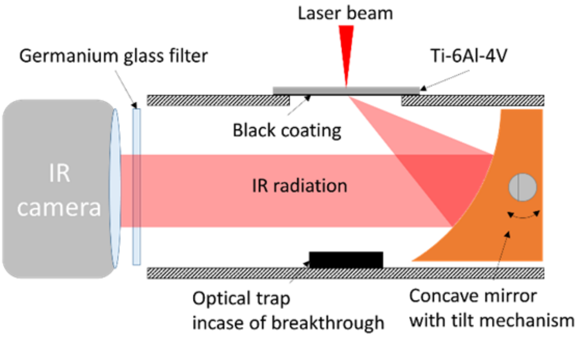

Fig. 2 IR thermography setup

III. RESULTS AND DISCUSSION

The developed temperature profile at the rear-side of titanium was assessed while irradiating the laser beam in the four conditions described in Table I. Results of the thermograph (Fig. 3) shows the temperature profile resulted by varying the laser power. It can be seen that increasing the power input has an effect on the maximum temperature and the width of the temperature profile. Moreover, high values of input power (parameters 4) demonstrate a plateau at the peak temperature.

Fig. 4 shows the effects of varying the welding speed. At this level of power (60 W), increasing the welding speed from

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700 mm/s to 900 mm/s resulted in a decline in maximum temperature reached, but no significant impact on the width of the temperature profile. The time profile of the four tested parameters shown in Fig. 5 describes the effects of process parameters on the cooling rate. Results show comparable cooling rate as demonstrated by the parallel contours in the graph. However, parameter 4 demonstrates a plateau at the maximum temperature demonstrating longer cooling time at the maximum detected temperature.

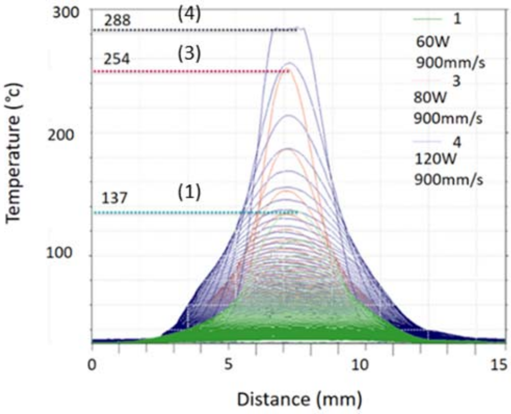

Fig. 3 Effects of varying laser power on spatial temperature profile

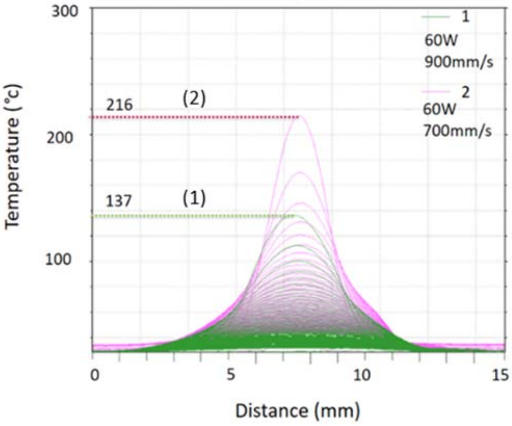

Fig. 4 Effects of varying beam speed on spatial temperature profile

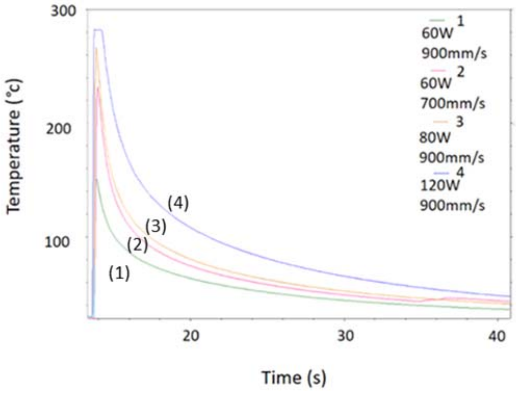

Fig. 5 Temporal thermography

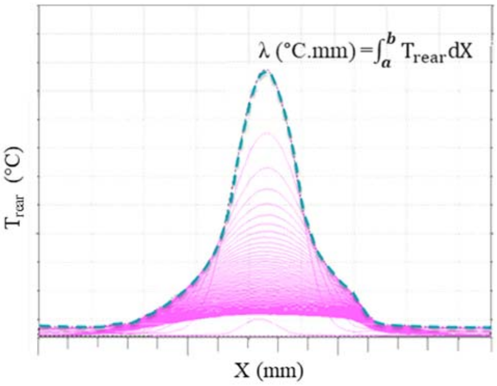

Fig. 6 Demonstration of area under graph (λ)

Although sound joint was achieved using parameter 1, thermography results show that the melting temperature of the polymer (260 °C as provided by the supplier (Dutec)) was not achieved at the rear-side of titanium given a maximum detected temperature of 137 °C, which does not allow the polymer to melt. Since thermography analysis was performed without the polymeric partner in place, it is expected that the actual interface peak temperature is different than the one reported. Therefore, another parameter characterizing the average temperature of the rear side, the temperature distribution parameter (λ (°C.mm) $=\int_{a}^{b} T_{rear} dX$) illustrated in Fig. 6, was used to describe the temperature profile, where a and b are 0 and 15 mm, respectively. Figures below show various correlations between the developed temperature profile parameter λ and energy density (Fig. 7), polyamide heat affected zone depth (Fig. 8), as well as titanium weld pool width (Fig. 9) and depth (Fig. 10). Direct correlations, described by the regression models on the graphs and their R2 values, suggests the reliability of this parameter λ in describing the joining process.

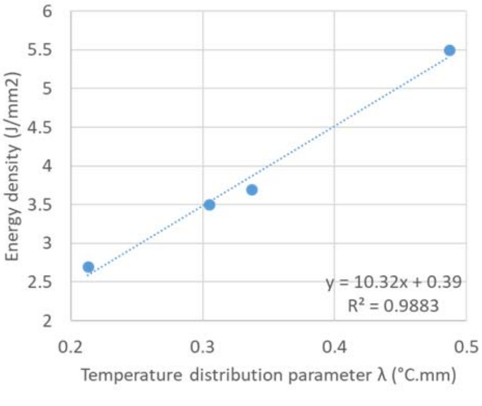

Fig. 7 Correlation between λ and energy density

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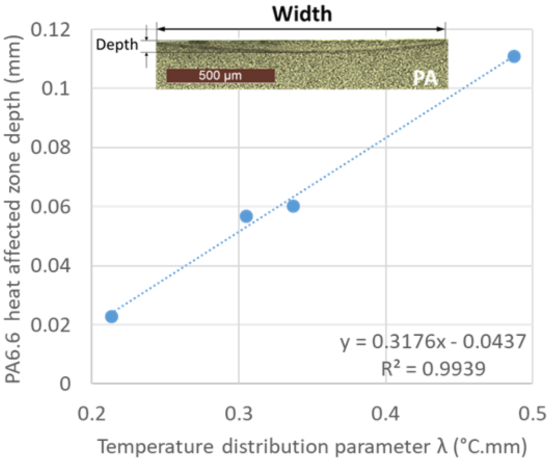

Fig. 8 Correlation between λ and polyamide heat affected zone depth

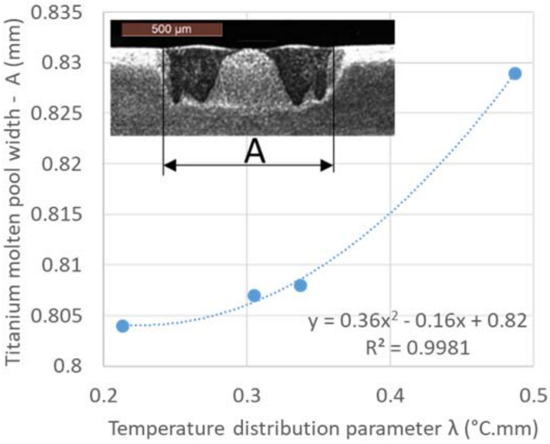

Fig. 9 Correlation between λ and titanium molten pool width

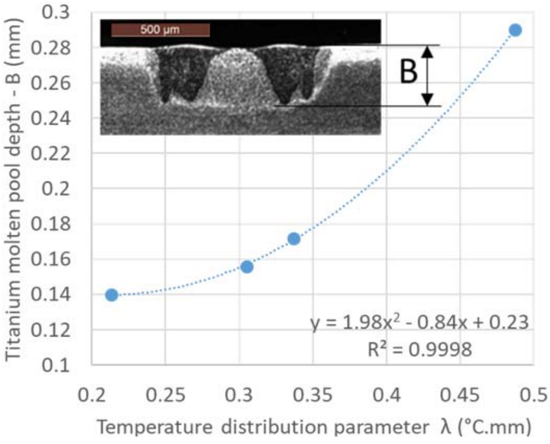

Fig. 10 Correlation between λ and titanium molten pool depth

IV. CONCLUSION

Assessment technique was developed to analyze the effects of laser welding parameters of titanium alloy (Ti-6Al-4V) to polyamide (PA6.6) on the interfacial temperature profile evolution in three dimensions, temperature, space, and time. Results show that increasing laser beam power results in an increase in the peak temperature and width distribution of the spatial temperature profile, and increasing the welding speed results in a decline in peak temperature with no effect on the width of the spatial temperature profile. However, varying laser irradiation parameters did not result in a significant difference on the cooling rate. In contrast to the welding process setup where the joining partners are clamped firmly in an overlap configuration, this technique requires removing the polyamide partner during assessment. This is expected to shift the measured peak temperature in comparison to that of the welding process. Thus, a temperature distribution parameter λ (°C.mm) was evaluated. Results show strong correlations between λ and the energy density of the welding process, as well as the weld pool width and depth in titanium, and the resulted polyamide heat affected zone depth, demonstrating the reliability of the developed assessment method. Furthermore, this method, through the λ parameter, provides a better description of the joining process.

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