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ABSTRACT

Nickel-based super alloy laser welding is of particular importance because of its numerous usages in the energy and aerospace industries. Measuring the temperature field is the basic criteria for conducting a qualitative evaluation of the weld joint. In this research, laser welding was experimentally investigated and the temperature field was measured. Measuring the temperature around the molten pool by varying the laser parameters such as nozzle distance, welding speed, laser power, and beam offset indicated a different heat field, resulting in changes in the molten pool's width and depth. Because of the high temperature of melting and low thermal conductivity coefficient of the Inconel 625 alloy, the measured temperature was large. Compared with the other parameters, the effect of enhancing the laser power on temperature increase around the molten pool was significant. The findings showed that, by increasing the laser power from 300 to 400 W, the temperature increased from 320 to 340 °C. Also, by increasing the nozzle distance from the surface of the workpiece to 2 mm, the temperature decreased from 300 to 200 °C.

Key words: super alloy, laser welding, temperature field, laser parameters, melting temperature

I. INTRODUCTION

The applications of laser welding in various industries such as nuclear, medicine, energy production, aerospace, and automobile have received much attention. In modern times, there is a need for industries to connect metals with mechanical strength and corrosion resistance at high temperatures, and this has resulted in significant challenges. A laser can weld a wide range of materials, just like conventional welding processes, if properly absorbed. The effectiveness of laser welding of metals and even nonmetals depends on several factors, including physical properties, which have a great impact on the absorption of laser beam energy and heat transfer rate.[1,2] These days, with the advancement of technology in the electro-optical industry, solid-state lasers, including fiber lasers, are used for welding applications in sensitive electronic or precision parts, to create a strong and convenient connection with the least amount of residual stress. The effectiveness of laser welding depends on the high power of the laser beam in a small area and the production of joints with different materials, regardless of the conductivity and thermophysical properties. The advantages of laser welding include excellent surface quality and less residual stress than other methods. This process has good repeatability due to a proper control of the heating and cooling cycle. Using different parameters of power, welding speed, and beam diameter, a suitable weld with excellent quality can be achieved compared with other methods. In laser welding, material properties such as thermal conductivity and laser beam absorption and workpiece material exercise a considerable influence on the effectiveness of the whole process.[3]

In recent years, the use of materials with different physical properties such as high strength at high operating temperatures has led to the development of new methods of bonding between metals, including nonferrous metals. Advances in new welding technologies, including laser welding, have improved the possibility of bonding for advanced materials, have led to significant improvements in the quality of joints and welding complex profiles, and have reduced the cost of laser welding.

Nickel-based superalloys have many applications in the aerospace industry for the manufacture of air or gas turbines blades. These alloys for welding require high applied energy density to achieve good mechanical properties. Park *et al.*[4] optimized the Inconel 617 superalloy laser welding using a tungsten arc welding method. The corrosion resistance properties and microstructure of the joint were optimized. The welding capability of the Inconel 617 thick sheet using a multipass welding method was investigated by Sun *et al.*[5] The welding parameters' effect on welding geometry and defects was investigated. Dendritic structure, grain size distribution, texture, crystal structure, and stress distribution were also investigated. Also, the mechanical properties of the joint were tested, including performing microhardness, tensile, and toughness tests at high temperature and ambient temperature. The results of the study indicated that the grain size was larger in the molten pool area. The values of microhardness and tensile strength at ambient temperature for the weld zone were higher than those for the base metal, and the tensile strength decreased with increasing temperature. Caiazzo *et al.*[6] performed butt-weld laser welding of the Inconel 625 sheet using a disk laser. They investigated the welding speed and laser power and their interaction effects on the factors governing welding conditions. To achieve a uniform weld, a special chamber was designed to supply gas and protect the molten pool. They indicated that the heat input value had an important role in the stability of the molten pool. It also affected the porosity and shape of the weld bead. According to the results, low amounts of input heat energy reduced porosity and led to the formation of a stable weld bead. The welding of Inconel 738 using a preheated heat treatment to compare the thermomechanical fatigue properties in the laser welding process with the nonwelded part was performed by Aina *et al.*[7] Due to the high cracking properties of this superalloy during welding, preheated heat treatment can increase the properties of thermomechanical fatigue resistance compared with the nonwelded part. The number of fatigue cycles for the Inconel 738 single-crystal superalloy was higher under the same strain conditions, although the failure mechanisms of both were the same. In another research, the fiber and CO_2 laser effect on the welding geometry and microstructure of the Inconel 617 alloy molten pool area was studied by Ren *et al.* [8] It was observed that the minimum input heat required for complete penetration of the weld in the fiber laser was much less than the CO_2 laser, and it could be said that the melting ability of the material in fiber laser welding was higher. Also, the microstructural changes in the molten pool were less due to the lower rate of input energy in the fiber laser. Lertora *et al.*[9] investigated the welding of the Inconel 718 alloy using a CO_2 laser. They investigated the mechanical properties and residual stresses due to welding operations and the fatigue life of the joint and compared them with the properties of the main material. They found that the molten pool area had a high tensile strength if the appropriate parameters were selected.

Kumar *et al.*[10] investigated the welding speed and laser power effects on the mechanical properties and microstructure of Inconel 617. Because of the high cooling rate, the microhardness of the molten pool area was higher than the heat-affected zone (HAZ). No cracks were found in the molten pool area due to freezing, although several overheated areas were found in the HAZ. Khorram *et al.*[11] investigated the laser soldering process of two materials, Inconel 600 and Inconel 718, using a nickel-based filler. Since Inconel 718 and Inconel 600 were known as a hard sediment and solid solution, respectively, it was soldered with a nickel-based filler (BNI-2) at different distances from each other. The results showed that the microstructure of the molten pool consisted of a solid solution of nickel, nickel boride, and chromium boride. In another study, the mechanical properties and microstructure in the laser welding of Hastelloy and Monel 400 superalloys were optimized by Kumar *et al.*[12] The primary microstructure consisted of a dendritic structure, although heat treatment resulted in a fine-grained microstructure. In comparison with the parameters, laser welding speed, pulse width, and pulse energy had the greatest effect on mechanical strength. The results of this research indicated that the molten pool's microstructure is remarkably dependent on the input energy. Mei *et al.*[13] investigated the welding speed effect on the microstructure of the molten pool and HAZ (hot cracking in the arc welding process). They found that the cross-sectional shape of the weld changed with increasing grain size of the base metal. Also, the lowest amount of microhardness was in the center of the molten pool. Ramkumar *et al.*[14] studied the mechanical properties and microstructure of 416 stainless steel and Inconel 718 superalloys using a CO_2 laser. The microstructure of the molten pond was free of any porosity and cracking. In the tensile section, failure occurred from the stainless-steel side, known as the base metal with weaker strength, although some microstructure defects were seen in the molten pool area during failure. Aminipour *et al.*[15] investigated the weld metal composition effect on the microstructure of dissimilar welding of Monel 400 and Inconel 600 alloys. In this process, tungsten arc welding with two groups of nickel-based and chromium-based fillers was used. The results showed that welding with nickel and chromium fillers will cause maximum and minimum tensile strength, respectively.

Pakniat *et al.*[16] investigated the heat treatment of hot cracking of a superalloy sheet (HASTELLOY-X). They used two types of pulsed and continuous lasers to perform the welding process. The results showed that prewelding heat treatment effectively reduced the likelihood of hot cracking. Also, in the process of pulsed laser welding, the tendency to crack was reduced by increasing the pulse laser frequency. Dissimilar laser welding of the Inconel 625 superalloy with 2205 stainless steel using fiber laser was performed by Ahmad *et al.*[17] By reducing the input energy rate, the weld bead became narrower and the welding mechanical properties improved. No cracks or cavities were observed in the microstructure of the molten pool. Tensile strength values indicated higher values of weld metal strength than those of base metal. Ghasemi *et al.*[18] studied the mechanical and metallurgical properties of a HASTELLOY nickel base superalloy in the tungsten arc welding process. The findings indicated that neither the molten pool area nor the HAZ had an adverse effect on the weld's mechanical properties.

On the other hand, microstructure changes and tensile residual stress due to heat stress applied by the welding process were partially reduced by heat treatment (postheating). In another study, multipass welding of the Inconel 600 superalloy using pulsed tungsten arc welding was performed by Srikanth and Manikandan[19] and the mechanical and metallurgical properties of the weld were evaluated. The results of the tensile test indicated that fracture had occurred in the welding joint. Also, the presence of some alloying elements such as titanium and molybdenum had improved the mechanical properties. Kumar *et al.*[20] studied the laser welding parameters' effect on the dissimilar laser welding process of nickel 201 alloy and S.S 316. The findings illustrated that laser power and welding speed were the two parameters affecting the weld's tensile strength. The beam angle had no significant effect on bead width and fusion zone area. Tungsten arc welding of Inconel 600 alloy was investigated by Kumar *et al.*[21] to reduce the chromium rate in the grain boundaries of this alloy. In this study, tungsten arc welding was performed using a chromium filler to prevent the phenomenon of chromium reduction in the grain boundary. In pulse laser welding, due to the high cooling rate, a cubic dendritic structure was observed in the molten pool area. Also, the obtained structure had become finer.

Laser welding of the Inconel 625 alloy was performed by Janicki *et al.*[22] using the laser diode with a rectangular beam profile for conduction mode welding for a sheet with a thickness of 0.8 mm. The welding parameter effects on welding quality and mechanical properties were studied. The results of the tensile test showed that the maximum tensile strength was 15% lower than that of the base metal. The effect of using an Inconel 625 filler on the microstructure and mechanical properties of Inconel 713 in the tungsten arc welding process was investigated by Tzeng and Wu.[23] Due to the different chemical compositions, the shape of the weld bead could be determined using the x-ray method. The process of cracking and shrinkage of the weld during freezing was directly related to the presence of different types of carbides in the grain boundaries. Liu *et al.*[24] investigated the mechanical properties and microstructure of laser welding of Ti6A4V and Inconel 718 alloys. They used a niobium-copper filler as the middle layer. Welding was performed in a combined soldering-welding mode, which included different metallurgical areas. The results of the tensile test indicated that weld failure had occurred at the connection point of the filler and Inconel 718 as a base metal. However, the addition of the niobium-copper filler had improved the mechanical properties of the joint.

Measuring the temperature during the process of laser welding can be a good way to study the changes in the melting rate of the material and its efficiency. Various research studies in the field of temperature measurement during laser welding of different materials have been performed experimentally and numerically. In this research, an experimental study of Inconel 625 alloy laser welding was performed. The novelty of this work lies in simultaneously investigating the laser welding parameter effects on the temperature field and the created temperature variation on the microstructural changes of the fusion zone and HAZ regions.

II. EXPERIMENTAL PROCEDURE

In this experiment, a fiber laser with maximum power equal to 500 watts was used to join two sheets of Inconel 625. The dimensions of the workpieces used were 50 × 25 × 1 mm.

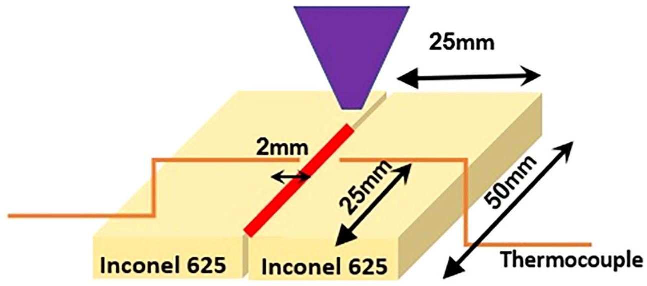

FIG. 1. The configuration of the experimental setup.

According to Fig. 1, K-type thermocouples with an accuracy of ±1% were placed at a 2 mm distance from the melt pool's center to record the temperature variations. An Advantech USB 4750 module card was utilized to save and process the temperature data. The chemical composition of Inconel 625 in weight percentages is shown in Table I.

The process of laser welding was conducted by fixing the sheets on a CNC table using a fixture. The laser parameter effects on the temperature field were studied. The mentioned parameters were power (P), welding speed (W.S), nozzle distance (N.D), and beam offset (B.O).

III. EXPERIMENTAL DESIGN

The level of parameters of laser welding is presented in Table II.

The changes in the laser parameters during the tests are presented in Table III.

The parameter of the beam offset represented the displacement of the beam from the interface (welded groove). An offset of +0.2 represented the beam displacement toward the left side, while an offset of −0.2 represented the beam displacement toward the right side. Furthermore, a zero offset indicated that the beam is applied to the center of the welded groove (interface). Figure 2 shows the laser beam offset during welding experiments.

IV. RESULTS AND DISCUSSION

In this part, the effect of working laser parameters such as power, welding speed, nozzle distance, and beam offset on the temperature field is discussed as follows. The temperature measurement around the melt pool effectively indicates variation of the welding condition.

A. Effects of laser parameters on the temperature field

1. Effect of welding speed

The rate of input energy per unit time always changes with changes in the laser welding speed. In this series of laser welding experiments performed at a fixed power of 350 W and at a nozzle distance of zero, by changing the welding speed from 300 to 500 mm/min, the temperature around the molten pool decreased to about 120 °C. As shown in Fig. 3, with a 40% increase in the laser

TABLE I. Material chemical composition of Inconel 625 used for the experiments (Ref. 17).

Composition	C	Cr	Nb	Ni	Ti	Mo	Mn	Si	V	W	Fe
% Weight	0.082	22.85	3.50	59.6	0.19	8.1	0.11	0.1	0.01	0.14	4.81

welding speed, the temperature also decreases by the same 40%. Therefore, changes in the rate of laser input energy per unit time were linearly related to the temperature. This temperature reduction rate for changing the speed of welding from 300 to 400 mm/min was not exactly linear but was lower. By increasing the welding speed from 300 to 400 mm/min, the temperature around the molten pool decreased by about 20 °C. It could be concluded that in the velocity variations from 300 to 400 mm/min, the rate of laser absorption and the physical conditions resulting from the interaction between the laser beam and the workpiece were variable. Also, due to the high penetration of the laser beam compared with the welding speed of 500 mm/min, the relation between temperature decreases and the welding speed was nonlinear, and other factors such as more beam absorption at higher temperatures and a higher melting volume gradually reduced the temperature around the molten pool. At a welding speed of 500 mm/min, due to the lower melting volume, the absorption of the laser beam and the formation of the molten pool had a linear relation with enhancing the welding speed value.

Also, it could be concluded that at a laser power of 350 W and at a focal length and welding speed of 500 mm/min, the welding conditions changed from keyhole mode to conduction mode. Therefore, the temperature changes in the conduction welding mode were linear, while the temperature changes in the keyhole welding mode were nonlinear. Furthermore, the temperature variations around the molten pool showed a nonlinear characteristic by changing the speed of welding from 300 to 400 mm/min. The main reason for this was that the laser beam penetrated into the molten pool and led to the formation of the keyhole phenomenon and the formation of plasma during welding. Also, the absorption of the laser beam in the molten material significantly increased, which was mainly due to the greater penetration of the beam in the molten pool at a low welding speed.

2. Effects of laser power

Laser power is an effective parameter in creating the molten pool and increasing the temperature around the molten pool. Figure 4 shows that enhancing the laser power from 300 to 400 W increases the temperature from 320 to 340 °C. Therefore, it can be said that increasing the laser power has the greatest effect on increasing the temperature around the molten pool. By always increasing the laser power, the beam's penetration depth and the dimensions of the molten pool become larger and cause a greater increase in temperature than when changing the other parameters. Figure 4 shows that with increasing the laser power at a speed of welding of 300 mm/min and at a nozzle distance of zero, the increase in temperature is greater than the change in the other parameters.

With increasing the power in the range of 300–400 W, the trend of temperature increase has been linear. This indicates that in a situation where the welding speed is 300 mm/min and the nozzle distance is equal to zero, no change in welding mode is observed and welding is always done in keyhole mode. Also, the effect of laser power reduction is also seen at a welding speed of 300 mm/min and at a nozzle distance equal to zero in Fig. 5. By decreasing the laser power from 300 to 250 W, the temperature decreases from 230 to 190 °C. It can be said that power changes in the range of examined parameters have a linear relation with temperature changes. On the other hand, it can be concluded that with changing the laser parameters, such as laser power, the Inconel 625 superalloy has a direct relation with the changes in the temperature around the molten pool and welding mode.

TABLE II. Level of laser parameters used in the tests.

Parameter	Welding speed (mm/min)	Power (W)	Nozzle distance (mm)
Level variation	300–500	200–400	−2 to 4

3. Effects of nozzle distance

In general, the distance of the nozzle from the surface of the workpiece and its changes indicate the variations of the laser beam diameter on the workpiece surface and consequently the change in the energy density of the laser beam on the surface of the workpiece. Therefore, changing the nozzle distance has a direct effect on the energy density and temperature around the molten pool and

TABLE III. Laser parameters used in the welding tests.

Exp (No)	Welding speed (mm/min)	Power (W)	Nozzle distance (mm)	Beam offset (mm)
1	300	400	0	0
2	300	300	0	0
3	300	350	0	0
4	300	350	+4	0
5	300	350	+2	0
6	300	350	−2	0
7	300	350	0	+0.2
8	400	350	0	0
9	500	350	0	0
10	300	250	0	0
11	300	350	0	−0.2

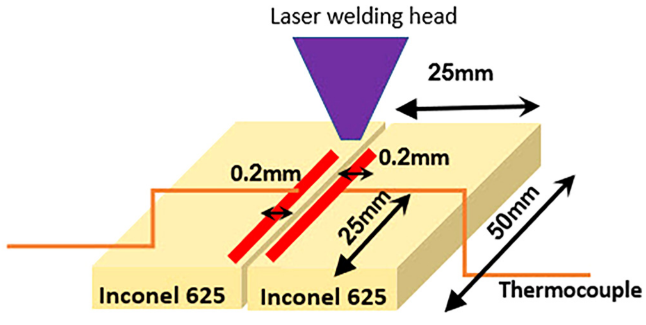

FIG. 2. Configuration of the laser beam offset.

the dimensions of the pool and the amount of its penetration into the workpiece. Figure 6 shows that with increasing the nozzle distance from the surface of workpiece at 350 W and at a welding speed of 300 mm/min, the temperature around the molten pool has decreased significantly. At the focal point, due to the high energy density, the temperature around the molten pool is about 300 °C, and by increasing the nozzle distance from the surface of the workpiece to 2 mm, the temperature has decreased from 300 to 200 °C. A further increase in the nozzle distance from 2 to 4 mm has only reduced the temperature from 200 to 180 °C (20 °C). It can be said that changing the focal length by changing the nozzle distance from the workpiece surface and increasing the nozzle distance by 2 mm increases the laser beam diameter on the workpiece surface and, thus, reduces the energy density and changes the welding mode from keyhole to conduction.

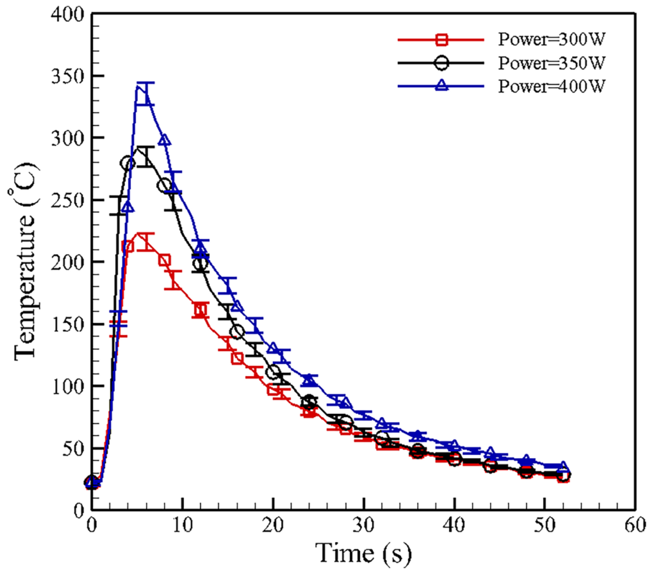

FIG. 4. Power effect on the temperature at W.S = 300 mm/min, N.D = 0, and B.O = 0.

On the other hand, further increasing the nozzle distance from the workpiece surface has reduced the temperature. This can be attributed to the fact that because of the presence of the fiber laser beam in the range of 5 mm outside the focal length, minor changes occur in the beam diameter. Therefore, the change in the

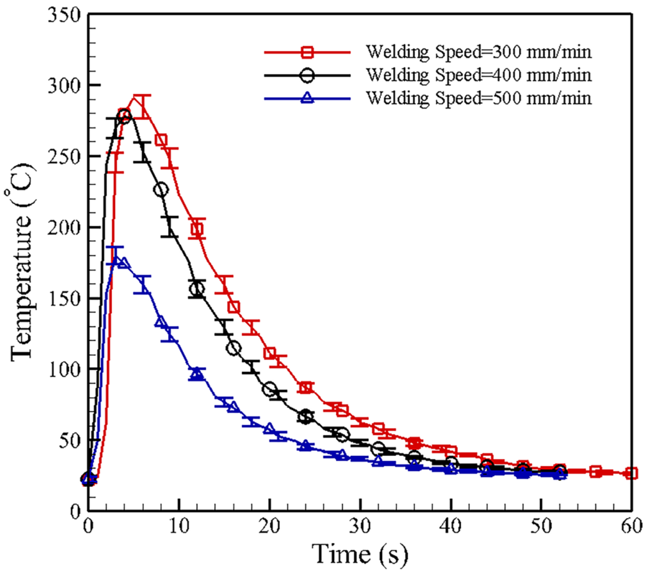

FIG. 3. Welding speed effect on the temperature at *P* = 350 W, N.D = 0, and B.O = 0.

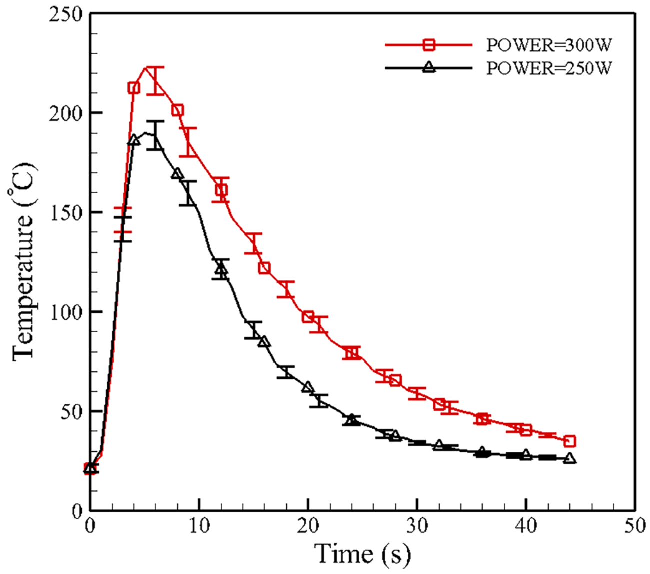

FIG. 5. Power reduction effect on the temperature at W.S = 300 mm/min, N.D = 0, and B.O = 0.

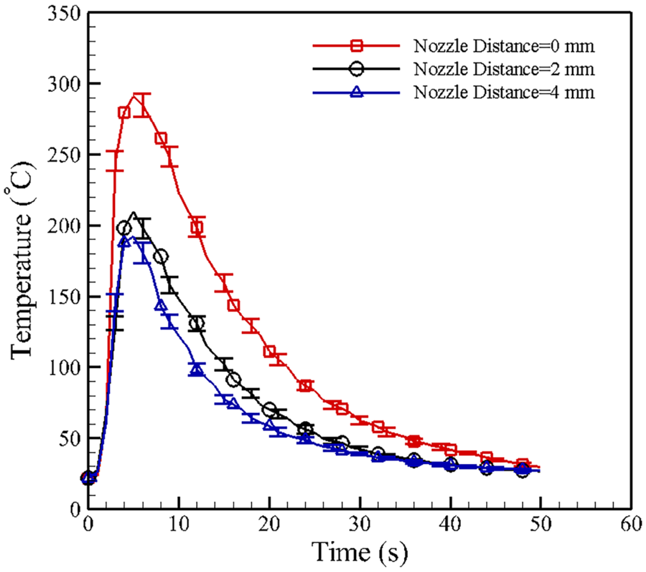

FIG. 6. Nozzle distance effect on the temperature at W.S = 300 mm/min, P = 350 W, and B.O = 0.

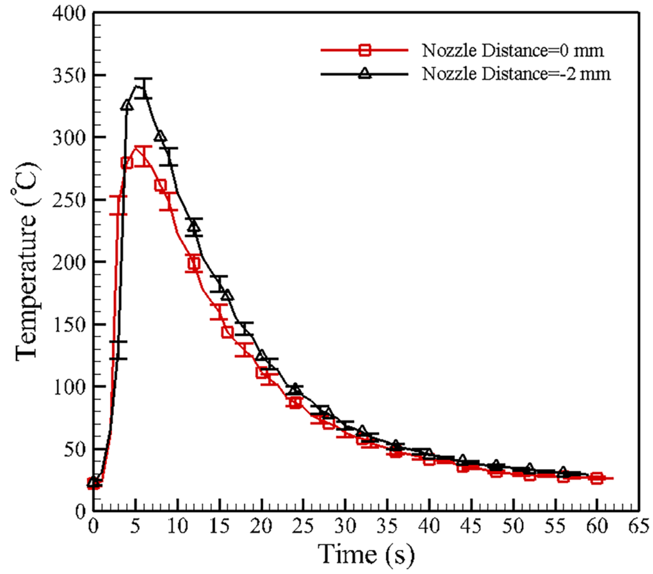

FIG. 7. Nozzle distance reduction effect on the temperature at W.S = 300 mm/min, P = 350 W, and B.O = 0.

energy density outside the focal point and up to a distance of 5 mm outside the focal point will be less and, therefore, the rate of temperature changes will be less too. It can be said that laser fiber has the highest energy density at the focal point and changes from the focal point to a certain distance (about 5 mm) depending on the type of optical system used, causing only minor changes in beam diameter and input energy density.

Due to the transfer of the focal point of the laser beam to the lower layer of the workpiece surface, the rate of temperature changes around the molten pool, as shown in Fig. 7. The figure shows that reducing the nozzle distance from the workpiece surface and transferring the focal point to the bottom of the workpiece and also transferring the focal point into the molten pool have all led to an increase in the temperature. Therefore, it can be said that by transferring the focal point and transferring the maximum amount of energy density to the inner and lower layers of the workpiece, the rate of melting and penetration in the lower layers of the workpiece surface has increased and the temperature has enhanced by about 50 °C.

4. Effects of beam offset

Figure 8 clearly shows the notable variation of the temperature measured by the thermocouple at the same place when the laser beam deviates from the point of contact between the two pieces. Due to the change in the maximum energy of the laser beam by changing the distance from the temperature measuring point, the variation in the measured temperature values highly depends on the distance from the thermocouple tip. This figure shows that in welding at the point of contact between two pieces at a welding speed of 300 mm/min and a power of 350 W, the temperature is about 270 °C. As the beam approaches 0.2 mm toward the thermocouple where the temperature is measured, the temperature increases by 40 °C. Therefore, the transition of the maximum energy point to a location closer to the thermocouple increases the temperature.

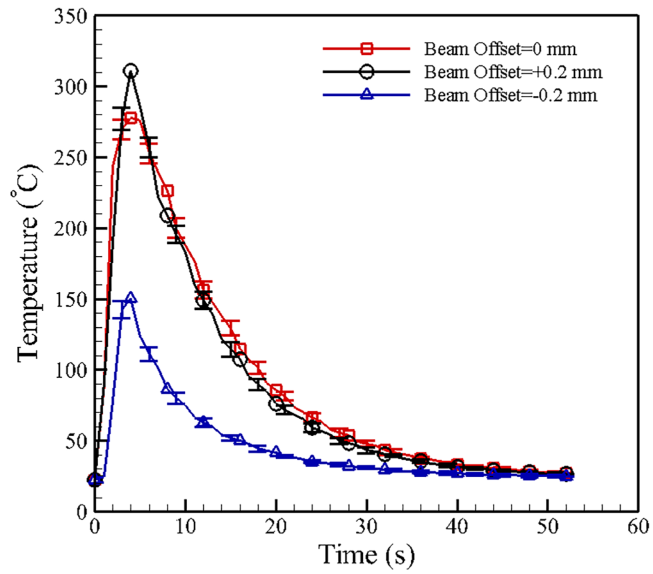

FIG. 8. Beam offset effect on the temperature at W.S = 300 mm/min, P = 350 W, and N.D = 0.

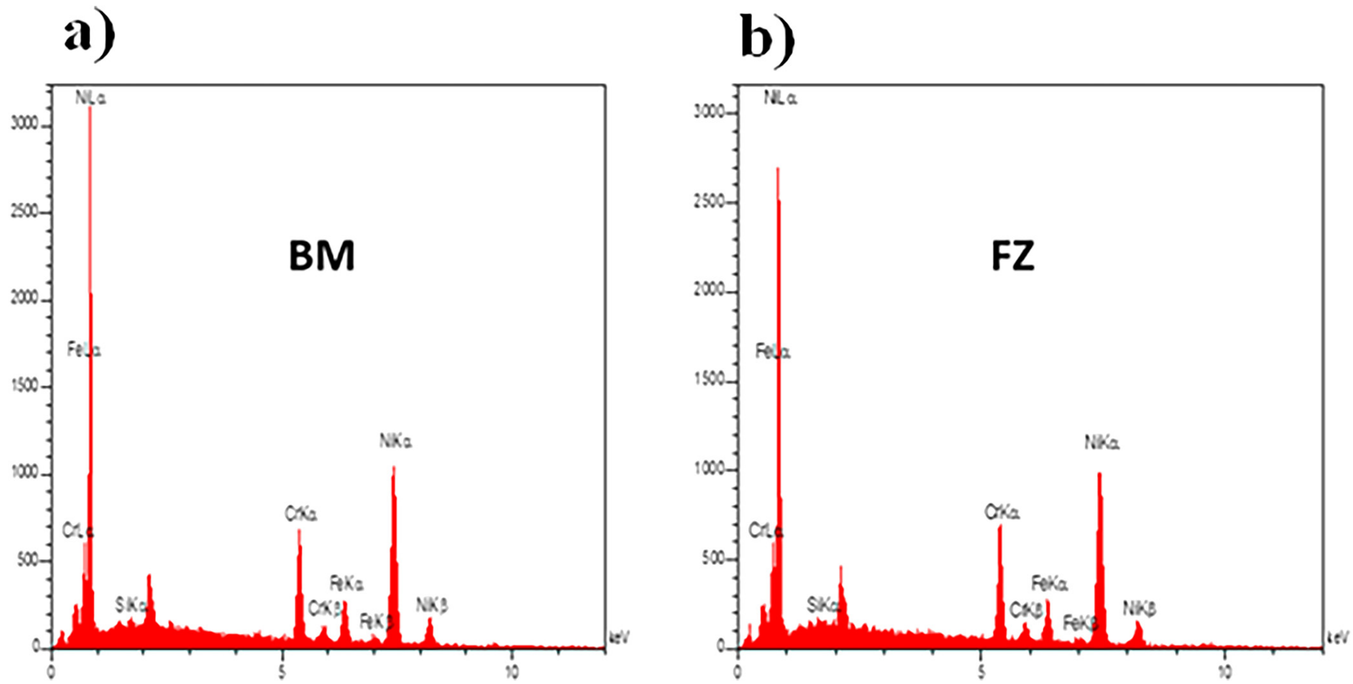

FIG. 9. Results of x-ray diffraction spectroscopy in (a) Inconel 625 base metal and (b) molten pool.

On the other hand, by transmitting the laser beam from the contact point of two pieces to 0.2 mm at a distance farther from the measuring point of the same thermocouple (opposite place), its measurement by the thermocouple is reduced by about 50%. It can be said that by deflecting the beam and transferring the focal point to another part (transfer of the maximum energy point to another part has caused a sharp decrease in temperature in the other part), a large volume of molten pool is created in another part and a maximum temperature is created in the opposite part. Therefore, the temperature around the molten pool has decreased significantly where a lesser part of the laser beam is exposed on its surface; the welding mode has changed from keyhole to conduction. As a result, a major part of the laser beam and the main part of the molten pool are in another part and their temperatures have greatly reduced. On the other hand, by transmitting the beam to a place closer to the thermocouple, the volume of the molten pool in that part has increased, and as a result, keyhole welding has been created with a larger molten pool and the temperature has increased to about 320 °C.

B. Elemental and microstructural analysis of the base metal to the molten pool

The results of x-ray diffraction (EDS) spectroscopy test showed that there was little change in the elemental weight percentage from the base metal to the weld zone and the HAZ (Fig. 9). It could be said that due to fixing the laser beam, creating a high thermal gradient, and using argon shielding gas, not many elemental changes in terms of elemental weight percentage from the base metal to the molten pool occurred. Table IV presents the percentage changes in the weight of each element, and it could be concluded that very small changes from the base metal to the molten pool occurred. Therefore, it could be said that only microstructural changes occurred due to the welding process.

Electron microscopy images showed simultaneous changes in the microstructure of the base metal, HAZ, and the molten pool. As can be seen in Fig. 10, there are obvious microstructural changes from the base metal to the HAZ and finally to the molten pool.

TABLE IV. Percentage of weight changes of Inconel 625 elements in the base metal and molten pool.

Element	Percentage of weight (base metal)	Percentage of weight (molten pool)
Ni	75.19	75.75
Fe	9	8.56
Cr	15.47	15.39
Si	0.34	0.29

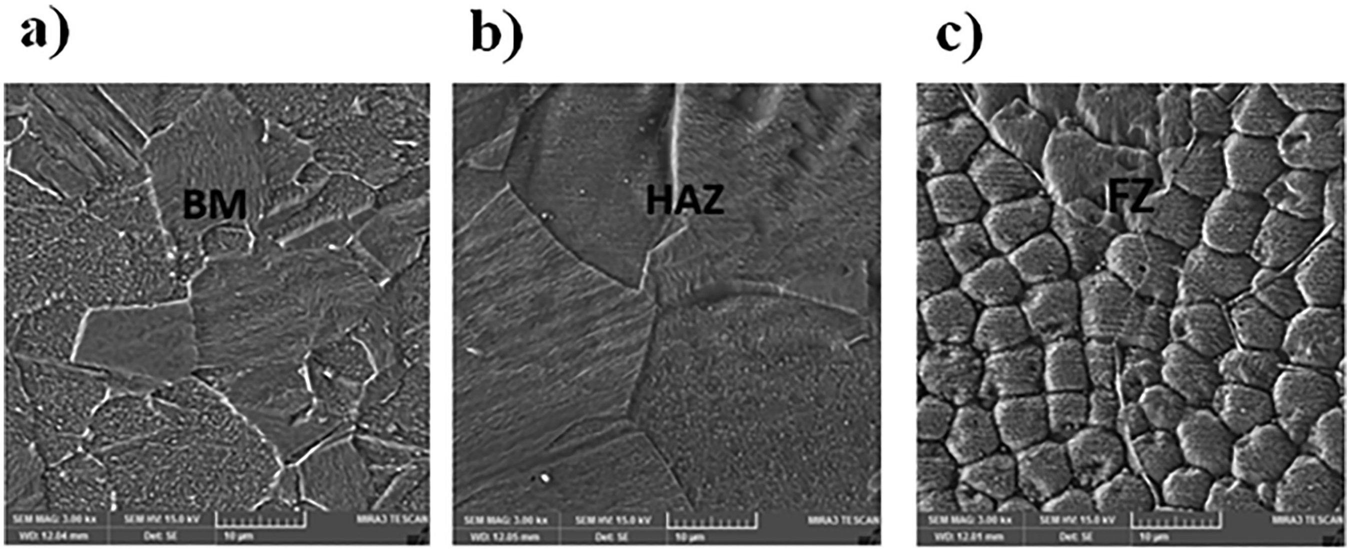

FIG. 10. Comparison of the SEM images of microstructure at the same magnification (a) base metal, (b) HAZ, and (c) molten pool of Inconel 625.

V. CONCLUSION

- When $P = 350$ W and N.D = 0 and W.S = 500 mm/min, the welding conditions changed from keyhole mode to conduction mode.
- The temperature variations near the molten pool of the Inconel 625 superalloy in the conduction welding mode were linear, while the temperature changes in the keyhole welding mode were nonlinear.
- As the laser power enhanced from 300 to 400 W, the temperature increased from 220 to 340 °C. Therefore, it could be said that increasing the laser power had the greatest effect on increasing the temperature around the molten pool. By always increasing the laser power, the penetration depth of the beam and the dimensions of the molten pool become larger and cause a greater increase in temperature than when changing the other parameters.
- Due to the high energy density at the focal point, the temperature around the molten pool was about 300 °C, and by increasing the nozzle distance from the workpiece surface, the temperature decreased from 300 to 200 °C. A further increase in the focal length from 2 to 4 mm only reduced the temperature from 200 to 180 °C (20 °C).
- Changing the focal length as a result of changing the nozzle distance from the workpiece surface and increasing the focal length by 2 mm increased the laser beam diameter on the workpiece surface and, thus, reduced the energy density and changed the welding mode from keyhole to conduction.
- The results of the x-ray diffraction (EDS) spectroscopy test showed that not many changes occurred in terms of the weight percentage of elements from the base metal to the molten pool.

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