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The Wear Treatment by Nd:YAG Laser on Ti–6Al–4V Alloy: Effect of the Spot Size on Laser Beam and Seam Morphology

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Due to the excellent corrosion resistance, high strength to weight ratio and high operating temperature, titanium and titanium alloys lead to successful application in various fields including the medical and aerospace industries. Among the reliable treatments techniques, laser weld can provide a significant benefit for the titanium alloys because of its precision, rapid processing capability and controlling the parameters with their effects. The Nd:YAG laser parameters, such as spot size and shape, pulse energy and duration, travel speed, peak power and frequency of repetition, influence directly or synergistically the quality of pulsed seam welds and their morphology. In this study, 1.5 mm thick titanium Ti6Al4V alloy sheet surfaces are treated by SigmaLaser®300 type Nd:YAG pulsed laser. The influence of spot size on seam morphology and effects to the surface are investigated. The seam and surface quality is characterized in terms of weld morphology and microhardness.

Завдяки відмінній корозійній стійкості, високому відношенню міцности до ваги та високій робочій температурі титан і титанові стопи знаходять успішне застосування в різних галузях, включаючи медичну й аерокосмічну промисловості. Серед надійних методик оброблення лазерне зварювання може забезпечити істотну перевагу для титанових стопів через його точність, можливість швидкого оброблення та контроль параметрів. Параметри Nd:YAG-лазера, такі як діяметер та форма зварної плями, енергія та тривалість імпульсу, швидкість подавання, пікова потужність і частота повторення, безпосередньо або синергетично впливають на якість швів імпульсного зварювання та їх морфологію. В цьому дослідженні поверхня листа титанового стопу Ti6Al4V завтовшки у 1,5 мм оброблювалась імпульсним Nd:YAG-лазером типу SigmaLaser®300. Досліджено вплив діяметра зварної плями на морфологію шва та впливи на поверхню. Якість шва і поверхні описано в термінах морфології зварного шва та мікротвердости.

Благодаря отличной коррозионной стойкости, высокому отношению прочности к весу и высокой рабочей температуре титан и титановые сплавы находят успешное применение в различных областях, включая медицинскую и аэрокосмическую промышленности. Среди надёжных методик обработки лазерная сварка может обеспечить существенное преимущество для титановых сплавов из-за её точности, возможности быстрой обработки и контроля параметров. Параметры Nd:YAG-лазера, такие как диаметр и форма сварного пятна, энергия и длительность импульса, скорость подачи, пиковая мощность и частота повторения, непосредственно или синергетически влияют на качество швов импульсной сварки и их морфологию. В данном исследовании поверхность листа титанового сплава Ti6Al4V толщиной 1,5 мм обрабатывалась импульсным Nd:YAG-лазером типа SigmaLaser®300. Были исследованы влияние диаметра сварного пятна на морфологию шва и воздействия на поверхность. Качество шва и поверхности описаны в терминах морфологии сварного шва и микротвёрдости.

Key words: Nd:YAG laser welding, spot size, surface treatment, Ti6Al4V alloy.

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1. INTRODUCTION

Titanium and its alloys have been widely used due to low density, good corrosion resistance, high operating temperature, *etc*. Some applications of titanium alloys in aerospace, biomedical, nuclear and automotive industries are well known [1, 2]. Ti6Al4V is the most famous titanium alloy, which, because of high strength, low thermal conductivity and high chemical reactivity, has difficult conventional machining and welding [3]. Although Ti6Al4V alloy is widely used as an implant material for load-bearing and non-load-bearing implants due to its excellent biocompatibility and corrosion resistance, its low hardness and poor wear resistance are still serious concerns. Majority of intended implant applications of Ti6Al4V alloy does not require very high wear resistance [4]. Laser is being used to solve these problems. Joining Ti6Al4V titanium alloys using pulsed Nd:YAG laser welding method was done by Akman *et al.* [5]. Their results showed that it was possible to control the penetration depth and geometry of the laser weld bead by precise controlling of the laser output parameters. Blackburn *et al* [6] produced the welds with high internal quality in Ti6Al4V using laser source as a welding technique. They observed the common periodic behaviours in the vapour plume and keyhole in low porosity welding conditions.

The special features and potential of laser welding technique has many benefits. The primary advantages include high scanning velocity, narrow heat-affected zone (HAZ), low distortion, excellent controllability and the ability to produce a high-intensity heat source, which is suitable for precision welding [7]. During the wear treatment applications, a small molten pool is formed by each laser pulse and, within a few milliseconds, it re-solidifies. When the pulse frequency is lower, welding occurs in conduction mode and a shallow and smooth molten pool is produced. But, when the pulse frequency is increased, a much deeper and wider pool is obtained. Changed seam morphology effected to surface form and hardness as well [8].

The formation and the quality of laser seam welds are the results of a combination of various pulsed-laser processing parameters, such as the travel speed, the average laser power, the pulse energy, the pulse duration, the average peak power density and the spot area [9]. This abundance gives control of the thermal input with a precision not previously available and permits a wide range of experimental conditions to be applied. On the other hand, controlling of so many parameters increases the complexity of laser processing [10].

In this study, the effect of pulse frequency on laser weld seams, employed by SigmaLaser®300 Nd:YAG laser system on 1.5 mm thick Ti6Al4V alloy has been investigated. To evaluate the effect of surface formation on the titanium alloy, 0.2 mm focal depth was determined for acceptable results, which is commonly used for repairing of the cutting or moulding tools.

2. EXPERIMENTAL AND THEORETICAL DETAILS

In this study, for wear treatment by blind welding, seams on small shaped ($40\times20\times1.5$ mm^3) Ti6Al4V titanium alloy sheets were chosen. The welding processes have been employed using SigmaLaser®300 Nd:YAG laser system. The pulse duration determined as 0.4 ms and pulse repetition was chosen as 28 Hz. The power rates were adjusted as 30% of 13 kW (3.9 kW). In the experiment, circle shape pulse has been applied to all workpieces. The chemical composition in weight percentage of the titanium substrate is shown in Table 1.

The laser beam is focused on titanium plates, the spot sizes on the plates were adjusted from 0.2 mm to 1.4 mm. During welding application, the laser beam has been focused on 0.2 mm under the surface of the plates to obtain sufficient power density. The laser output parameters are varied in the experiment as shown in Table 2.

For analysis of the microstructures after the applications, the workpiece weld seams were prepared for optical microscopy using standard procedures of grinding, polishing and etching. Sandpaper (P200-, P400-, P800- and P1200-grit) was used for the grinding and solutions (3 μm and 6 μm) for the polishing.

Microhardness measurements were performed according to the seam dimensions and values were obtained from the heat-affected zone

TABLE 1. The chemical composition of Ti6Al4V.

Material	C	Fe	N_2	O	Al	V	H	Ti
Content	<0.08%	<0.25%	<0.05%	<0.15%	5.5%	3.5%	<0.03%	balance

TABLE 2. Applied laser parameters.

Parameter	Values
Pulse frequency	28 Hz
Peak power	3.9 kW
Pulse duration	4 ms
Spot size (∅, mm)	0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4
Welding speed	50 mm/min
Focal depth	–0.2 mm
Gas and pressure	Argon (99.8%) at 1.5 bar

(HAZ). Furthermore, a scanning electron microscopy (SEM) analysis was carried out to observe the morphology and surface of the weld seams.

3. RESULTS AND DISCUSSION

Previous studies have shown that all parameters such as peak power, spot size, pulse frequency, pulse duration, welding speed and focal depth are affecting the seam morphology and properties. Spot size is one of the key parameters for the pulsed laser system. For seam geometry and surface hardness, it is crucial to control the pulse energy, in addition to the laser power, spot size, pulse length, and pulse repetition.

All parameters related to each other and welding or wearing properties. Any change of parameters for pulsed laser system, welding geometry, penetration depth, surface morphology and other properties are effected. If the melt pool is too large or too small, or if significant vaporization occurs during welding, unsuccessful results can be obtained. Therefore, the control of laser power, pulse repetition, pulse length and spot size are very critical. Penetration depth is increased with increase of peak power, pulse repetition as heat input. However, narrower spot size is also increases the penetration depth because of the concentration of the energy.

Figures 1–7 show the seam morphology of the welded specimens welded under the peak powers of 3.9 kW and from 0.2 mm to 1.4 mm spot sizes. During the applications, laser beam has been focused on 0.2 mm under the surface and beam spot diameter is 0.8 mm on the surface of the workpiece. The pulse duration has been kept constant for each welding parameter as 4 ms.

In previous studies, during the regular laser welding process, the spot size was determined as ≅ 0.1–0.7 mm for Ti–6Al–4V alloy [3–7]. A narrower fusion zone is an effective parameter, which allows the laser energy concentration to reach a deeper penetration for welding applications, in addition to causing less welding distortion. Owing to observation of the effect of fusion zone, different spot sizes were employed and the results in this study were investigated.

As illustrated in Figs. 1–7, it has been found out that while changing the spot sizes, the seam morphologies have also changed. At the larger spot sizes, smaller grains sizes and the martensitic structures occurred on the seams, because of the rapid cooling.

The focal depth parameter of laser applications as –0.2 mm is very common for surface treatment and for the repair of cutting and mould-

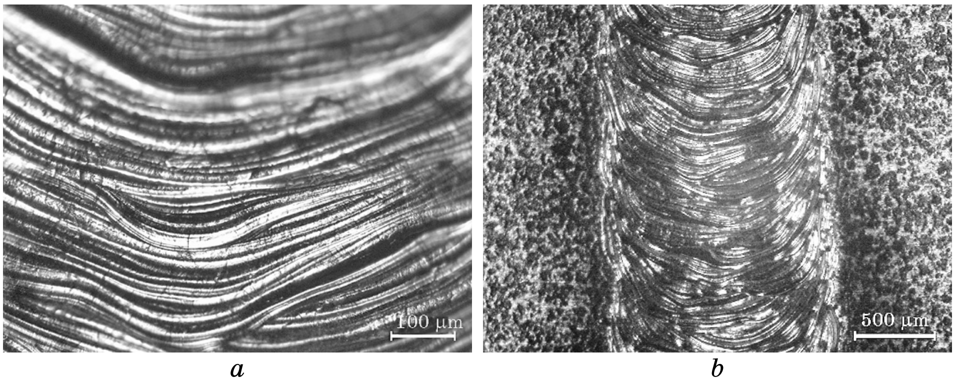


Fig. 1. 0.2 mm spot size of weld seams.

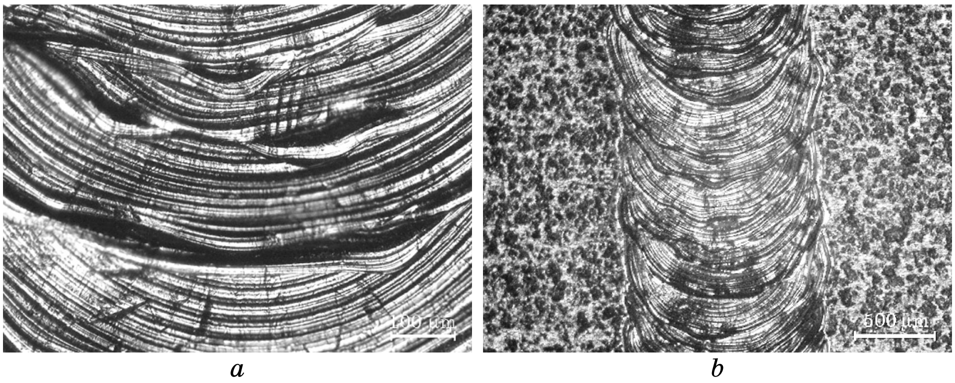
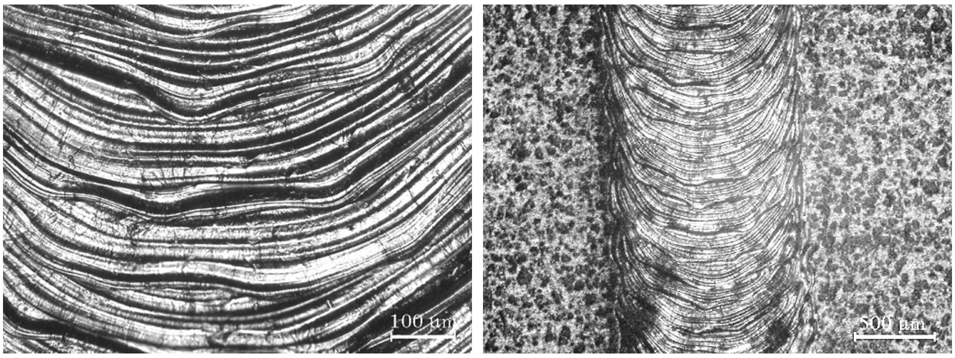
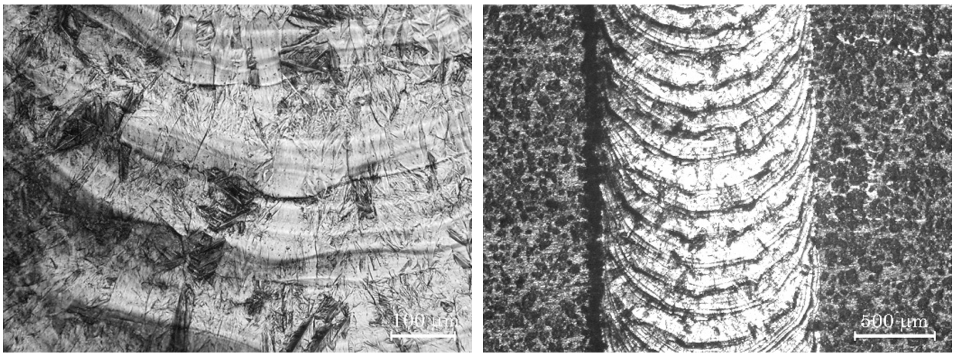


Fig. 2. 0.4 mm spot size of weld seams.



a *b*

Fig. 3. 0.6 mm spot size of weld seams.



a *b*

Fig. 4. 0.8 mm spot size of weld seams.

ing tools. The shallow seams are increasing the cooling rates and rapid cooling rates cause the occurrence of the martensite structure which is desired achievement of surface hardness.

Pulse duration is another effective parameter for heat input. For welding applications, it is necessary to increase heat input for penetration depth. Longer pulse duration causes higher heat input. However, in this study, in order to obtain a harder surface for wear treatment, the heat input was limited, and the pulse duration was determined as 4 ms.

Based on previous studies [5, 8], the peak power was optimized as 3.9 kW. During the applications, the energy was transferred by means of a laser beam. If higher energy is used, much deeper penetration can be achieved. This is not desirable for surface treatment as the material can melt and vaporize. Higher transferred energy affects material loss, which occurs in the weld pool and appears as a deep crater formation.

Measured seams width is approximately constant (between 1.3 mm

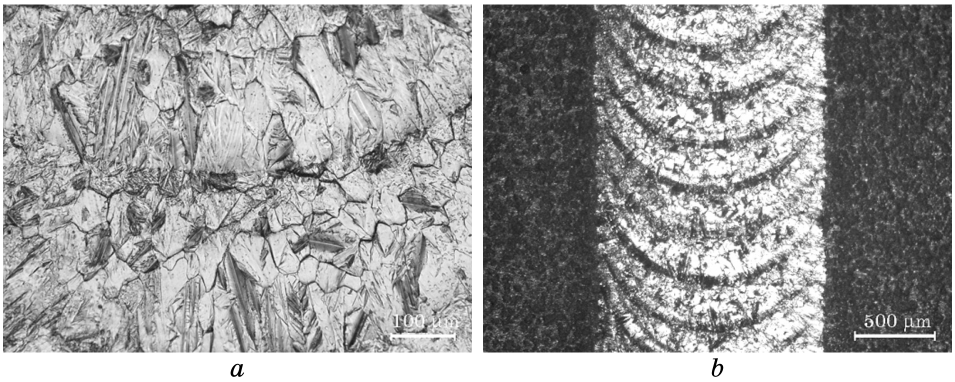


Fig. 5. 1.0 mm spot size of weld seams.

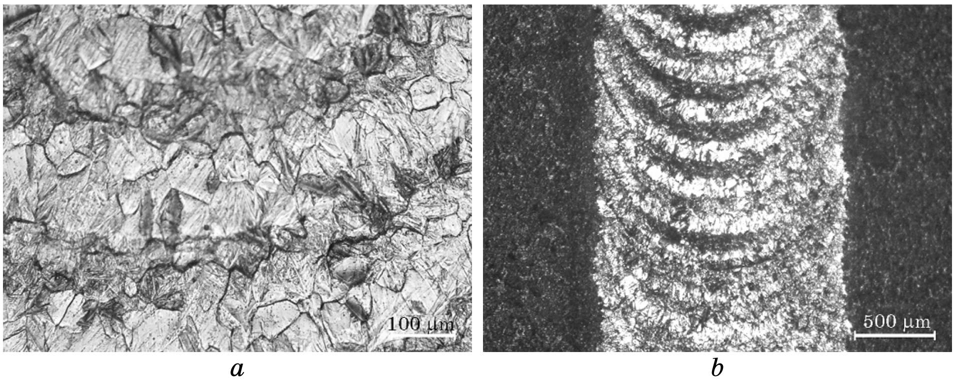


Fig. 6. 1.2 mm spot size of weld seams.

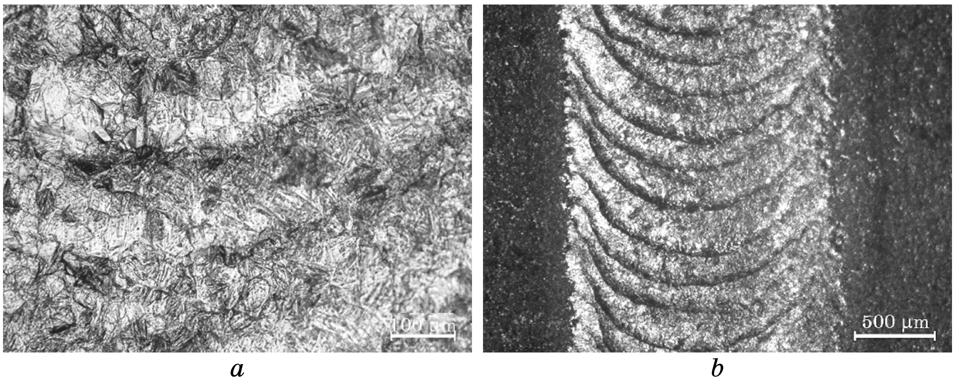


Fig. 7. 1.4 mm spot size of weld seams.

and 1.8 mm). This result can be explained with the beam concentration effected the seam depth more than their width. The penetration depth and HAZ are also related to laser peak power and beam concentration. The plasma absorption is very strong at the top of the weld (at the surface of the material), where the available laser energy is high; it leads to increasing of the weld pool and HAZ width larger than spot size (see Figs. 1–7). The same effect has been reported by Weldingh and Kristensen [11].

There is always a cracking risk due to the rapid cooling of the welded joint [5]. At high temperatures, titanium is reactive with ambient gases. For this reason, and to protect against atmospheric effects during welding, argon (99.8%) shielding gas was used at 1.5 bar to protect the melted pool and HAZ from oxidation until solidification was sufficient. Therefore, it was crucial to use the shielding gas and to set up the nozzle in order to prevent the formation of turbulence on the sample surfaces during the application.

The main reasons of the porosities are trapping of some of the gases within the solidifying weld pool as determined [12]. During the laser welding process, formation and solidification of the melted material, hydrodynamic movements in the melted material (vortex formations) are the factors affected on size and dispersion of porosity illustrated in Figs. 8, 9.

It is seen on the figures from cutaway of the blind seam as longitudinal section and cross section in different magnifications. The seam depth, its morphology, and wear effect of laser beam can be observed from the figures above. The oxide layer on surface and right below the porosities then HAZ, which has the focal depth of –0.2 mm, is demonstrated in Figs. 8 and 9.

The size or geometry of seams and dispersion of porosity are related also to the laser parameters (pulse energy, duration, shape, repetition rate, and peak power), type of assisting gas used and nozzle design.

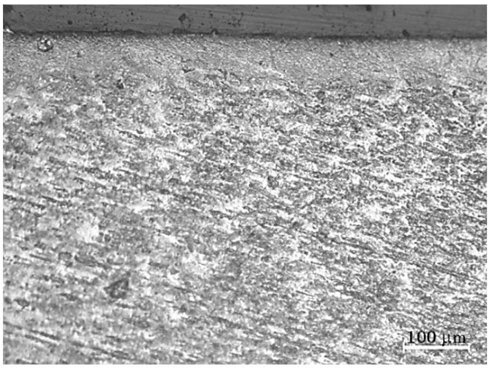
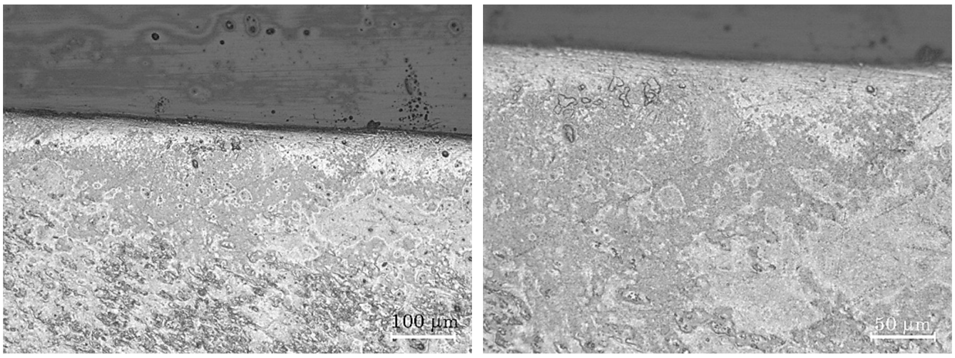


Fig. 8. Longitudinal-section and seam morphology.



a *b*

Fig. 9. Cross-section of HAZ and porosities.

Pulse repetition, pulse duration and the pulse energy have been increased in order to obtain deeper penetration without any loss on the surface. The deepest penetration has been obtained at 0.2 mm spot size, which has more beam concentration (pulse duration was fixed as 4 ms).

The hardness distributions of the welds have been analysed using a SHIMADZU HMV microhardness tester with a load of 100 g. The microhardness test has been carried out at the surface of seams on the centreline of the weld pool, heat affected zones as border of the seam and work pieces, as HAZ of specimens. As a result, at the transition zone of the weld seams, the hardness is in the maximum level and the melted and cooled material is remarkable compared to the base metal due to its rapid cooling rate (see Fig. 10).

The observed large increase in hardness in laser welded Ti–6Al–4V is caused by high cooling rate associated with laser beam welding. The high cooling rates cause the formation of martensite in the weld zone of HAZ region. It is reported by Sundaresan and Janaki [13] that rapid cooling and subsequent martensitic transformation are effective strengthening methods for many titanium alloys.

In previous studies for wearing the surface by continuous wave Nd:YAG laser, the average hardness of melted region was higher by 15–22% than the average hardness of Ti6Al4V alloy substrate [4]. In this study, it has been reached to 50–300% higher than base metal hardness in melted region by Nd:YAG pulsed laser. The difference in hardness between the transition zone and the base metal is over 700 *HV* in narrower spot size parameters. Different welding techniques such as electron beam and gas tungsten welding techniques, which were applied on Ti6Al4V alloys in previous studies [14, 15], have shown that high power density of laser beam welding provides a lower heat input and a more rapid solidification when compared to the conventional techniques, so laser welding technique leads to higher hard-

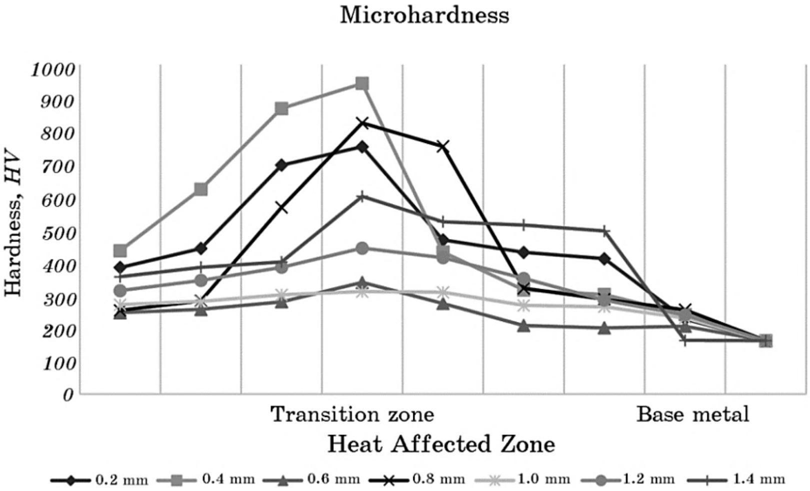


Fig. 10. Microhardness distribution of three workpieces for different spot sizes.

ness values. In heat-affected zone, the cooling rate is higher in transition zone than in weld pools. The difference between the transition zone and base metal is over 800 *HV* in 0.2 mm to 0.8 mm spot sizes.

Higher beam concentration by smaller spot sizes, increased the target temperature producing steeper thermal gradients and severe thermal straining [16]. It was expected that reducing the spot size causes the narrower seam and increases the cooling rate and hardness. Therefore, it was obtained in this study while increasing the beam concentration, penetration depth and surface hardness were also increased.

Another result of the study shows the effect of laser treatment and shielding gas on the surface of workpieces. It is seen in Figs. 11, *a*, *b*.

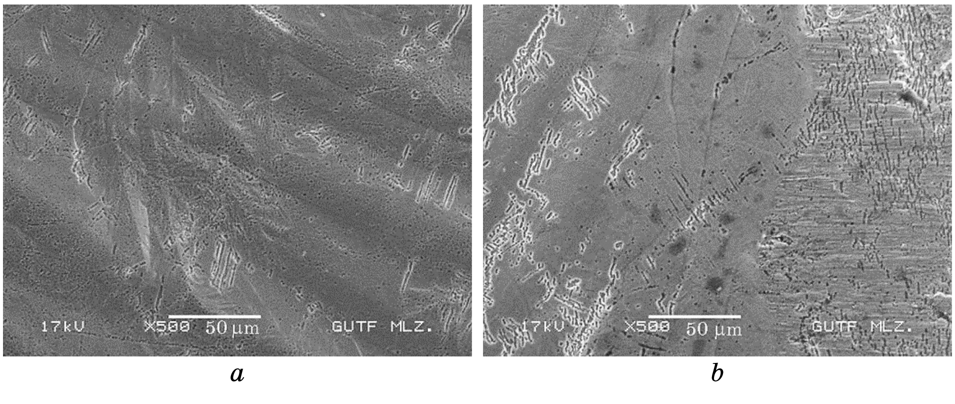


Fig. 11. Effect of the laser and shielding gas on seam surface. Seam surface (*a*); seam and base metal surface (*b*).

In Figure 11, *a*, there is little oxidation and burned gas seen on the seam surface. It can be cleaned by very simple process. However, if you see the Fig. 11, *b*, there is seen the seam and base metal surface and the surface cracks and oxide layer seen on the base metal surface clearly. Laser treated on Ti4Al6V titanium alloy surface has excellent results such as hardening and removing or repairing the surface cracks on the base metals remains from manufacturing.

4. CONCLUSIONS

The Nd:YAG pulsed laser welding technique has been employed to join Ti6Al4V titanium alloys as blind seams for surface treatment. As it is seen in the results, satisfactory surface properties were obtained from the experiments, such as hardening and repairing of surface cracks and possible to control the seam morphology and geometry of the laser weld by controlling the laser output parameters. It has been known that peak power is the most important parameter while determining the penetration depth, width. Nevertheless, for surface treatment, the peak power not only parameter to get higher hardness values. The heat input and cooling rates are related to other parameters such as beam concentration by spot size, pulse energy per pulse duration and pulse repetition as frequency. In this study, the effect of spot size was investigated on the laser seams. Narrower spot size increases the beam concentration and it causes harder surfaces, especially on transition zones. The optimum level of spot size in this study was founded as 0.8 mm. Nevertheless, at the over and lover of the optimum level, some surface cracks, more martensitic structures, and craters were seen. At the optimum level, the seam morphology and wear properties were in excellent conditions as desired.

The concentration of the beam directly related to spot size parameters, which is one of the most effective parameters for wear treatment applications. As it is known, all parameters related to each other for Nd:YAG laser welding and wear treatments such as peak power, spot size, pulse frequency, pulse duration, focal depth and weld speed. This study shows that it is possible to control in one parameter to the seam morphology, while stable the others. To increase the penetration depth, spot size should be decreased.

Owing to the rapid cooling rates of laser applications, the microhardness profile across the weldment indicates that the hardness distribution in the fusion zone is higher than both the HAZ and parent metal in all parameters. However, the hardness values are higher at transition zones more than weld pools, which are related to more cooling rate.

For obtaining the optimum values of hardness on the surface of TiAl4V alloy, 3.9 kW peak power, 50 mm/min welding speed, and 28

Hz pulse frequency were chosen as they were shown in previous studies as better parameter for tool repair applications [8]. The other parameters, such as shallow focal depth as –0.2 mm for the material and its geometry, and 4 ms pulse duration, which is limited for the Ti6Al4V, caused to obtain the sufficient results and hardness on workpieces. This study shows that any Nd:YAG laser weld parameters gave a chance to increase of the surface hardness, better wear properties.

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