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Research Article

Effect of Pulse Repetition and Peak Power of Nd:YAG Laser for Surface Treatment on Ti–6Al–4V Alloy

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ABSTRACT

Titanium and titanium alloys have led to a diversified range of successful application in various fields including the medical and aerospace industry due to the high strength to weight ratio and excellent corrosion resistance. Several techniques have been considered to achieve reliable welds and treatments for the fabrication of components in these industries. Among these techniques, laser welding can provide a significant benefit for the welding of titanium alloys because of its precision and rapid processing capability. The Nd:YAG laser parameters, such as pulse shape, energy, duration, welding speed, peak power and frequency of repetition, influence directly or synergistically the quality of pulsed seam welds and it's morphology. In this study, 1.5 mm thick Ti6Al4V Titanium alloy sheet surface have been treated by SigmaLaser®300 type Nd:YAG pulsed laser. The influence of peak power and pulse frequency on weld quality, seam morphology and effects to the surface have been investigated. The seam quality has been characterized in terms of weld morphology and micro hardness.

Keywords: *Nd: YAG laser, Surface treatment, Ti6Al4V alloy*

Nd:YAG Lazer ile Ti–6Al–4V Alaşımı Yüzey İşlemlerinde Atış Tekrarı ve Pik Gücünün Etkisi

ÖZET

Titanyum ve Titanyum alaşımları, yüksek mukavemet, düşük ağırlık oranı ve mükemmel korozyon direnci sebebiyle, medikal ve havacılık endüstrisi dahil olmak üzere birçok alanda başarıyla kullanılmaktadır. Bu alanlarda yapılan üretimler için uygulanan kaynak ve iyileştirme işlemleri için birçok teknik mevcuttur. Bu teknikler arasında, lazer kaynağı hassas ve hızlı işlem kabiliyeti sayesinde Titanyum alaşımları için çok önemli avantajlar sağlamaktadır. Darbe ya da atış şekli, enerji, süre, kaynak hızı, pik gücü ve frekans gibi Nd:YAG lazer parametereleri, doğrudan ya da dolaylı olarak kaynak dikiş kalitesini ve morfolojisini etkilemektedir. Bu çalışmada, 1.5 mm kalınlığında Ti6Al4V Titanyum alaşımı levha yüzeyi SigmaLaser®300 Nd:YAG tipi lazer kaynak cihazıyla işlenmiştir. Pik gücü ve frekans değerlerinin kaynak kalitesine, dikiş morfolojisine ve numune yüzeylerine etkisi incelenmiştir. Dikiş kalitesi, morfoloji ve mikro sertlik değerleri bakımından karekterize edilmiştir.

Anahtar Kelimeler: *Nd: YAG lazer, Yüzey iyileştirme, Ti6Al4V alaşımı.*

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I. 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 [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. Laser is used to solve this problem. Also, Ti6Al4V can be welded using a PW and CW laser. Several studies on the effect of different welding parameters in laser welding of Ti6Al4V have been conducted experimentally and numerically [3]. Joining Ti6Al4V titanium alloys using pulsed Nd:YAG laser welding method was done by Akman et al. [4]. Their results showed that it was possible to control the penetration depth and geometry of the laser weld bead by precisely controlling the laser output parameters. Blackburnetal [5], produced the welds with high internal quality in Ti6Al4V up to 3.25mm in thickness by using laser source as a welding technique. They observed the common periodic behaviors in the vapor plume and keyhole in low porosity welding conditions.

The special features and potential of laser welding technique has many benefits in comparison with conventional thermal joining processes. 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 [6].

During the 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 weld pool is produced. But when the pulse frequency is increased, a much deeper and wider weld pool is obtained.

The laser seam welding, as a series of overlapping spot welds to form a fusion zone or seam. The formation and the quality of 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 [7]. This abundance gives control of the thermal input with a precision not previously available and also permits a wide range of experimental conditions to be applied. On the other hand controlling so many parameters increases the complexity of laser processing [8].

In this study, the effect of pulse frequency and peak power on laser weld seams, on 1.5 mm thick Ti6Al4V has been investigated, using the SigmaLaser®300 system Nd: YAG laser. To evaluate effect of surface formation and/or reduction in the titanium alloy, acceptable results can be obtained when the focus depth is 0.2 mm, which is used mostly for repairing the cutting or molding tools.

II. MATERIALS AND METHODS

In this study, for wear treatment blind welding of a small shaped (40 mm × 20 mm × 1,5 mm) Ti6Al4V titanium alloy sheets have been employed using SigmaLaser®300. Nd:YAG laser that has 0.4 ms pulse duration and 11 Hz, 14 Hz and 17 Hz repetition rate chosen. The system of SigmaLaser®300 has double pulse occurred with extra mirror for each repetition which means 22 Hz, 28 Hz and 34 Hz. The power rates were adjusted as %30, %40 and % 50 of 13kW. 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.

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

The laser beam is focused on titanium plates, the spot size on the plates has been 0.8 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 Table 2.

Table 2. *Applied parameters*

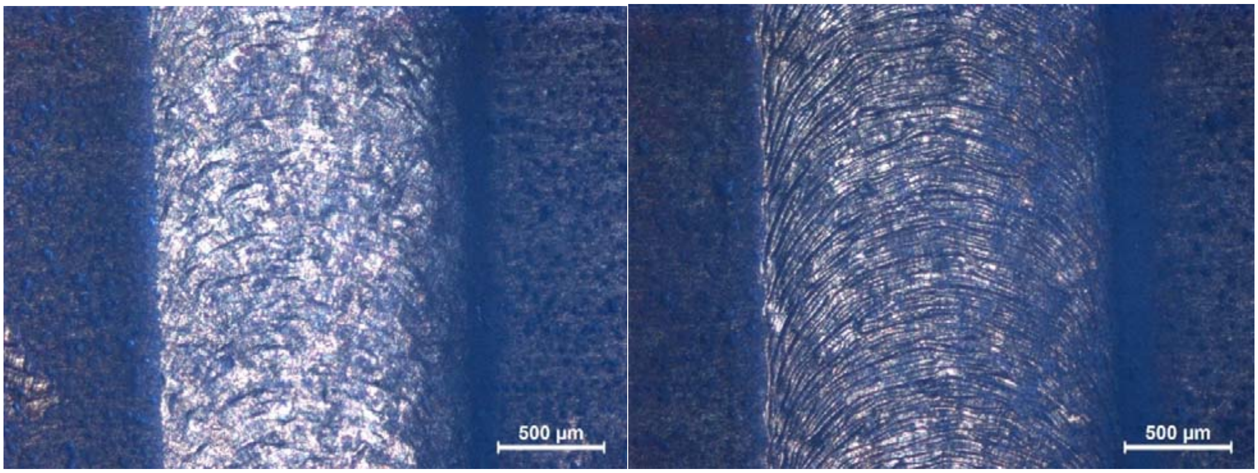
Parameter	**Values**
Peak Power (kW)	3.9 – 5.2 – 6.5 kW
Pulse Duration (ms)	4 ms
Pulse Frequency	22 – 28 – 34 Hz
Welding speed	50 mm/dk
Focal depth	-0.2 mm
Gas and pressure (bar)	(%99.8) Argon, 1.5 bar

After the applications, weld seams of workpieces have been prepared for optical microscopy using standard procedures including grinding, polishing and etching. For gridding P200, P400, P800 and P1200 type grids and for polishing 3 µm and 6 µm solution were employed. For measuring the laser heat effect the micro hardness were obtained from Heat Affected Zone (HAZ) and SEM analysis have also been examined to see the morphology and surface of weld seams.

There is always a cracking risk due to the rapid cooling of welded joint [4]. Titanium is reactive material at high temperature with ambient gases. For these reasons and also protecting to the atmosphere effects, during the welding application 1.5 bars % 99,8 Argon shielding gas has been used to protect the melt pool and HAZ from oxidation until sufficient cooling has occurred. At this point shielding gas usage and nozzle set up are very important, formation of turbulence on the sample surfaces must be avoided.

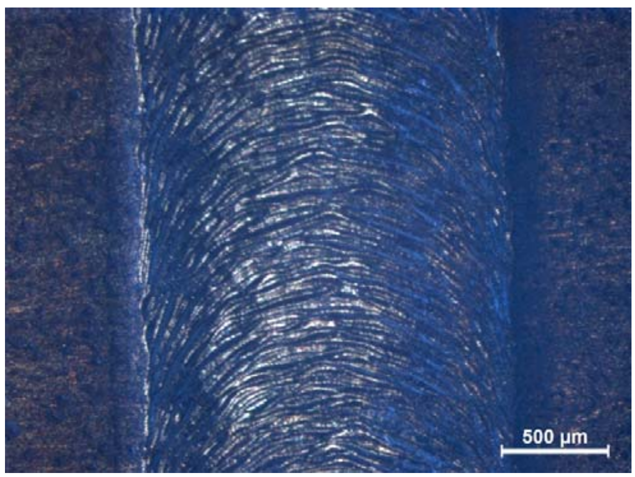
III. RESULTS AND DISCUSSION

The peak power and pulse frequency are critical parameters for pulsed laser system for welding geometry and other effects. 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 and pulse length are very critical. Penetration depth and seam width are increased with increase of peak power and pulse repetition as frequency as heat input. Fig. 1 a-b-c. show that the seam morphology of the welded specimens welded under the peak powers from 3.9 kW, 5.2 kW and 6.5 kW. During the applications, laser beam has been focused on 0.2 mm under from 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.



a) %30 Peak Power
34 Hz Pulse Repetition
1.3 mm Seam Width

b) %40 Peak Power
28 Hz Pulse Repetition
1.5 mm Seam Width



c) 6.5kW Peak Power,
22 Hz Pulse Repetition
1.6 mm Seam Width

Fig. 1 *Effect of peak power and pulse repetition on weld seams*

As illustrated in Fig. 1, it has been found out that the seam width has increased linear with the peak power. At higher peak power levels limitation at seam width increase is observed. It has been measured the seams approximately constant around 1.3mm by 3.9 kW, 1.5mm by 5.2 kW and 1.6mm by 6.5 kW. This result can be explained with plasma absorption of laser beam. The penetration depth, heat affected zone (HAZ) and weld pool width are also related to laser peak power. 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 enlarge the weld pool and HAZ width (see Fig. 1). The same effect has been reported by Weldingh and Kristensen [9].

During the regular laser welding process, spot size determined around 4 mm. Because of limitation for the fusion zone which effects the welding distortion. Narrower fusion zone is one of the best reason to choose the laser welding techniques. In this study, the spot size determined as 8 mm, which is not suitable for welding process, it’s for surface treatment such as repairing the surface and improving the properties.

And other parameter is focal depth which is determined as -0.2 mm in this study, which is most common parameter for surface treatment and repairing the cutting and molding tools. The shallow seams, such as -0.2 mm, increasing the cooling rates which creates the martensite structure and cause to surface hardness that desired. For welding process, it should be closer to workpiece thickness to reach optimum penetration to join the pieces.

The pulse duration is another effective parameter for heat input. For welding application, it’s needed to increase heat input for penetration depth. Longer pulse duration cause higher heat input. For average weld joints, which depends on the material and geometry, it should be around 10 ms for Ti6Al4V alloy [4]. In this study, to obtain of the harder surface heat input limited and pulse duration determined as 4 ms.

The crater formation occurs at high peak power levels at the top of the surface, highly focused energy is transferred by means of laser beam during the welding and this energy melts the material without vaporization. If the transferred energy is higher, the material loss comes up in weld pool and it is indicated as a crater formation with the depth.

The main reasons of the porosities are trapping of the some of the gases within the solidifying weld pool as determined [10]. 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 Fig 2.

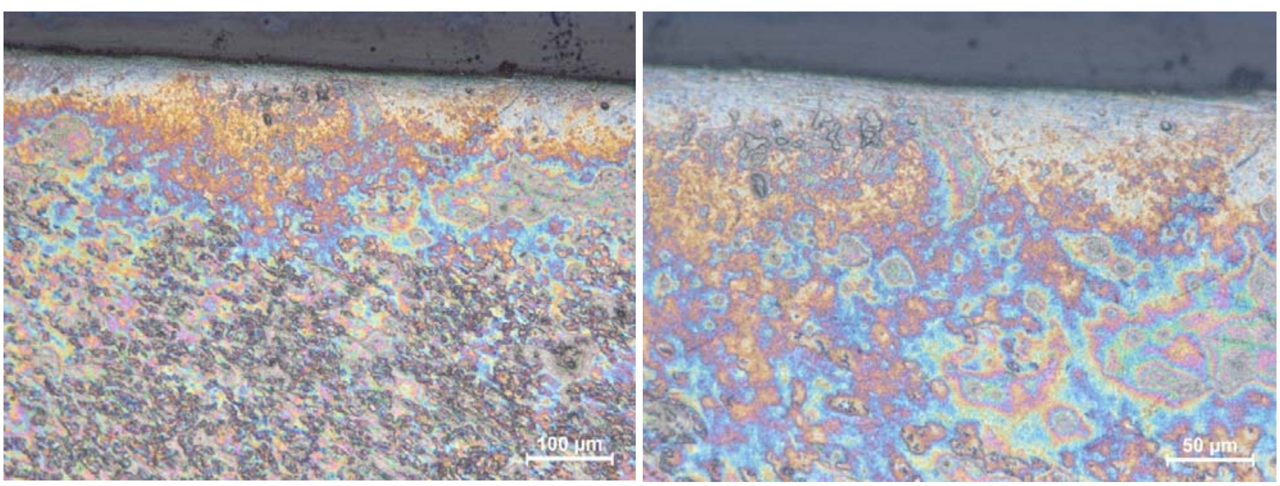


Fig. 2. *Cross-section of HAZ and porosities*

It’s seen on the figures from cutaway of the blind seam in different sizes that the oxide layer on surface and right below the porosities then HAZ which has the focal depth of -0.2 mm.

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. 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 6.5 kW peak power (pulse duration was fixed as 4 ms).

The hardness distributions of the welds have been analyzed using a SHIMADZU HMV micro-hardness tester with a load of 100 g. The micro-hardness test has been carried out at the surface of seams on the centerline 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 are 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. 3).

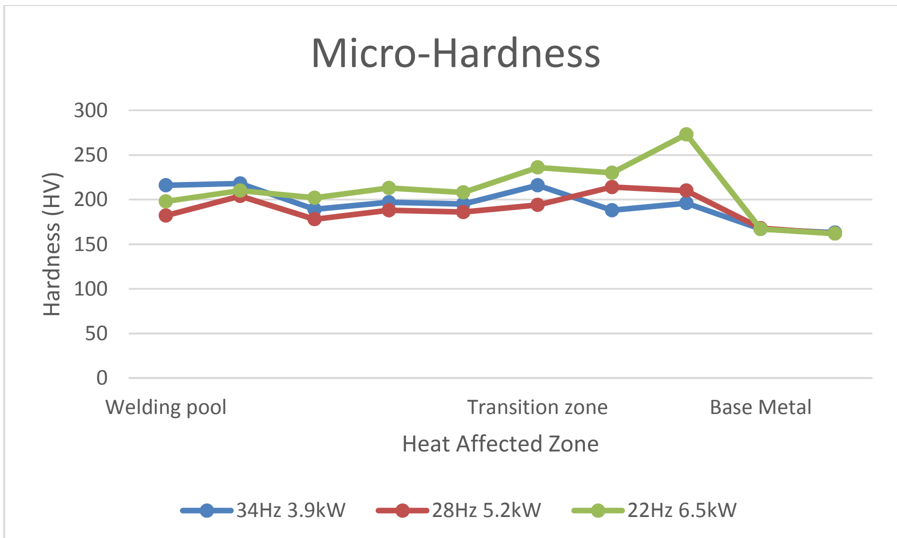


Fig. 3. *Micro-hardness distribution of three workpieces for different peak power*

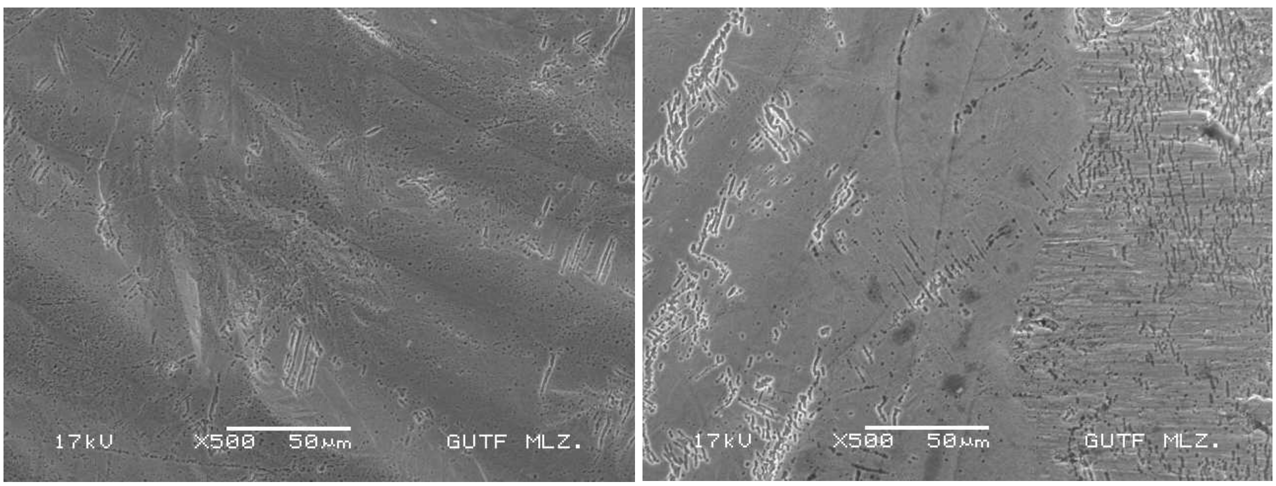
The observed large increase in hardness in laser welded Ti–6Al–4V is due to high cooling rate associated with laser beam welding. The high cooling rates cause the formation of martensite in the weld zone HAZ region. It is reported by Sundaresan and Janaki [11] that rapid cooling and subsequent martensitic 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 15–22% higher than the average hardness of Ti6Al4V alloy substrate [12]. In this study, it has been reached to 25-50 % higher than base metal hardness in melted region by Nd: YAG pulsed laser. The difference in hardness between the weld pool and the base metal, are about 40 to 80 HV. Different welding techniques such as electron beam and gas tungsten welding techniques are applied on Ti6Al4V alloys in previous studies [13, 14] 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 hardness values. In heat affected zone, the cooling rate is higher in transition zone than weld pools. The difference between the transition zone and base metal is around 110 HV in highest peak power (6.5 kW).

Higher heat input by peak power and other parameters, increase the target temperature producing steeper thermal gradients and severe thermal straining. So, the increase in average power increases total heat input to the target, but it’s expected that reducing the cooling rate as well as the temperature gradient and the hardness should decrease with increasing average power [4, 15].

The hardness values have similarities in weld pools for each parameters as peak power and pulse frequency, in this study. Owing to the parameters have been adjusted as optimum heat input rates, while increasing the peak power, the pulse frequency has been decreased intentionally. And as it's expected, the highest values of hardness have been obtained in transition zones. However, higher peak power caused more hardness values in transition zone, unexpectedly. As mentioned in previous studies, peak power is most effective parameters for laser applications as heat inputs and more heat input should cause to lower cooling rates. The results thought that peak power is not as effective parameter as pulse repetition for cooling rates. The hardness distributions of the welded materials are illustrated in Fig. 3 as a function of peak powers and as pulse repetitions.

Another result of the study shows the effect of laser treatment and shielding gas on the surface of workpieces. It's seen on the Fig 4 a-b.



a) Seam surface *b) Seam and base metal surface*

Fig 4. *Effect of the laser and shielding gas on seam surface*

In the Fig 4-a, there is little oxidation and burned gas seen on the seam surface. It can be cleaned by very simple process. But if you see the Fig 4-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 an excellent results such as hardening and removing or repairing the surface cracks on the base metals remains from manufacturing.

IV. CONCLUSIONS

The Nd: Yag pulsed laser welding technique has been employed to join Ti6Al4V titanium alloys as blind seams for surface treatment. The results show that there is satisfied surface properties such as hardening and repairing of surface cracks and also 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. But for surface treatment the peak power not only parameter to get higher hardness values. The heat input and cooling rates are also related to other parameters such as pulse energy per pulse duration and pulse repetition as frequency. In this study, the effect of peak power and pulse frequency investigated on the laser seams. Increasing the peak power, increases the heat impute but it causes to wider weld pool and higher cooling rates, especially on transition zones. The lower pulse frequency effected to cooling rates more than peak power in present results. If the peak power is increased more than optimum level, the temperature of the workpieces exceeds to the evaporation point of the Ti6Al4V alloy, which promotes the crater formation on surface of the materials as wider seams. Wider seams and lower pulse effected to rapid cooling rates and it caused higher level of hardness, especially in transition zones.

As it's known, all parameters related to each other. While increasing the peak power, the pulse frequency will have less limits which is for controlling the heat impute automatically. To increase the penetration depth or seam width, heat input should be increased by controlling the parameters. Owing to the rapid cooling rates of laser applications, the micro hardness 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 is related to more cooling rate. On the contrary of previous studies higher peak power caused to higher hardness in this studies, especially in transition zones.

For obtaining the higher values of hardness on the surface of TiAl4V alloy, spot size determined as 8mm which is larger than optimum level of the welding applications. The other parameters, such as shallow focal depth as -0.2 mm for the material and it's geometry and 4 ms pulse duration which is limited for the Ti6Al4V, caused to obtain the sufficient results and hardness on workpieces.

In the previous studies, the peak power was thought that the most effective parameters for weld seams. Any increase peak power increases total heat input to the target reducing the cooling rate as well as the temperature gradient. So the hardness should decrease with increasing average power. But in this study, while increasing the peak power and decreasing the pulse frequency caused to lower hardness. Lower pulse repetition effects rapid solidification and cooling rates increased to harness values. The results show that, pulse repetition is more effective than expected on cooling rate on Nd:YAG laser seams for surface treatment.

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