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Deformation and microstructural analysis of fiber laser and TIG welding of thin Ti6Al4V sheet by coordinate measurement machine (CMM)

İnce Ti6Al4V saçların fiber lazer ve TIG kaynağı sonrası koordinat ölçme makinası (CMM) ile deformasyonunun ve mikroyapısal analizinin yapılması

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Highlights

- *The mechanical and deformation properties of Ti6Al4V titanium alloy joints between a pulsed fiber laser source and a tungsten inert gas (TIG) welding were compared.*
- *The welded by fiber laser has narrow heat affected zone (HAZ), small overall residual distortion, fine microstructure, high Vickers hardness.*
- *Joining the Ti6Al4V sheet with the laser welding method is more mechanically favorable because of low heat input and high cooling rate can cause extreme hardness and brittleness in the material.*

Graphical Abstract

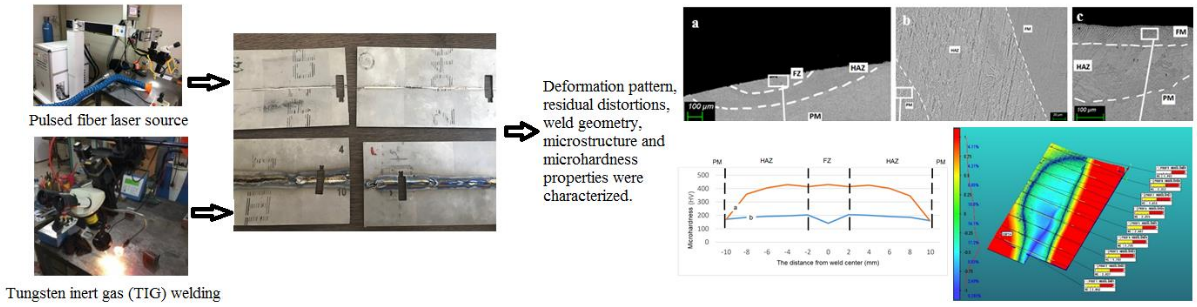

Figure. Deformation pattern, residual distortions, weld geometry, microstructure and microhardness properties of the joints produced with fiber laser source and tungsten inert gas welding were compared.

Aim

This paper reports on a study to compare the mechanical and deformation properties of Ti6Al4V titanium alloy joints between a pulsed fiber laser source and a tungsten inert gas (TIG) welding. Ti6Al4V alloy sheets - 0.8 mm thick-deformation modifications were investigated via a 3D laser scanner integrated to a portable-arm Coordinate Measurement Machine (CMM) and PC-DMIS software.

Design & Methodology

All specimens welded by pulsed fiber laser and TIG processes, have been scanned to inspect deformation amounts. HP-L.8.9 3D laser scanner integrated to Romer 7320 portable CMM and Pc-Dmis software have been used for acquiring data as point clouds. Specification of HP-L.8.9 3D laser scanner is given Table 3. CAD model of the specimens has been imported to Pc-Dmis and used as the reference for all 3D scanning operations.

Originality

Deformation pattern, residual distortions, weld geometry, microstructure and microhardness properties of the joints produced with fiber laser source and tungsten inert gas welding were compared. It is easily possible to detect the distortion amounts with 3D laser scanner after welding.

Findings

When compared distortion amounts of a specimen before and after welding both TIG and pulsed fiber laser welding specimens, remarkable distortion has been observed after welding. However, the distortion generated by fiber laser welding is much smaller as compared to TIG welding. The effect on the microstructure is less than that of the fused zone because the heat affected zone temperature is lower than the fused zone. The fused zone in the pulsed fiber laser welding also shows the presence of needle-like α_I martensite in along with acicular within the equiaxed grains.

Conclusion

Joining the Ti6Al4V sheet with the laser welding method is more mechanically favorable because of low heat input and high cooling rate can cause extreme hardness and brittleness in the material.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Deformation and Microstructural Analysis of Fiber Laser and TIG Welding of Thin Ti6Al4V Sheet by Coordinate Measurement Machine (CMM)

Araştırma Makalesi / Research Article

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ABSTRACT

This paper reports on a study to compare the mechanical and deformation properties of Ti6Al4V titanium alloy joints between a pulsed fiber laser source and a tungsten inert gas (TIG) welding. Ti6Al4V alloy sheets - 0.8 mm thick-deformation modifications were investigated via a 3D laser scanner integrated to a portable-arm Coordinate Measurement Machine (CMM) and PC-DMIS software. Deformation pattern, residual distortions, weld geometry, microstructure and microhardnes properties of the joints produced with fiber laser source and tungsten inert gas welding were compared. Compared with the TIG, the welded by fiber laser has narrow heat affected zone (HAZ), small overall residual distortion, fine microstructure, high Vickers hardness. It can be concluded that fiber laser welding is more suitable for welding the thin Ti6Al4V titanium alloy plate than TIG welding; due to the small beam focus characteristics of fiber lasers enabiling deep penetration welding.

Keywords: Fiber laser welding, joint properties, Ti6Al4V titanium alloy, TIG welding.

İnce Ti6Al4V Saçların Fiber Lazer ve TIG Kaynağı Sonrası Koordinat Ölçme Makinası (CMM) ile Deformasyonunun ve Mikroyapısal Analizinin Yapılması

ÖZ

Bu çalışmada, Ti6Al4V ince saçların kaynağında kullanılan darbeli fiber lazer ile tungsten ark kaynağı (TIG) arasındaki mekanik ve deformasyon özelliklerini karşılaştırmaya yönelik bir araştırma sunmaktadır. Ti6Al4V alaşımlı levhalar - 0,8 mm kalınlıkta - deformasyon ölçümleri için portatif Koordinat Ölçüm Cihazına (CMM) ve PC-DMIS yazılımına entegre edilmiş bir 3D lazer tarayıcı ile taranmıştır. Fiber lazer ve tungsten ark kaynağı kullanılan kaynak numunelerinde deformasyon paterni, artık çarpılmalar, kaynak geometrisi, mikroyapı ve mikro sertlik özellikleri karşılaştırılmıştır. TIG ile karşılaştırıldığında, fiber lazer ile kaynaklı numunelerde dar ısıdan etkilenmiş bölgeden (HAZ) dolayı, daha küçük deformasyonlara, ince mikro yapıya, yüksek Vickers sertlik ölçümlerine rastlanmıştır. Fiber lazer kaynağının Ti6Al4V alaşımına sahip levhaların kaynaklanmasında TIG kaynağından daha uygun olduğu sonucuna varılmıştır; Fiber lazerlerin küçük ışın odaklama özelliği sayesinde daha derin penetrasyon kaynağı sağladığı gözlemlenmiştir.

Anahtar Kelimeler: Fiber lazer kaynağı, kaynak özellikleri, Ti6Al4V titanyum alaşımları, TIG kaynağı.

1. INTRODUCTION

Ti6Al4V alloy is extensively used in manufacturing of the electric power industry, nuclear power, petrochemical, automotive, medical industry and the aerospace components because of the combination of high strength-to-weight ratio, low density, high stiffness, excellent fatigue properties, fracture toughness and good corrosion resistance [1]. In addition to all these, in recent years, Ti6Al4V sheets are particularly used in space laboratory chambers, air inlets, fuel tanks, and the titanium capsules that contain the Iodine-125 radioisotope used for cancer radiotherapy. Today, titanium alloys are an important part of the industry, while new technologies and applications for these alloys continue to evolve [2]. With increased applications of titanium alloys in the various industries, welding methods like friction welding, electron beam welding (EBW), laserbeam welding (LBW), laser hybrid welding, TIG welding have been developed and are widely used for the joining of titanium alloys for different applications [3-9]. Both conventional and solid state welding techniques are employed for joining of titanium alloys [10]. However, conventional arc welding is mostly used due to ease of automation and low cost operation [11]. Furthermore, laser welding has also proven to be very effective especially for titanium alloys due to its focused and dense heat source and low heat input

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resulting in narrow heat affected zone [9]. Laser welding has certain key beneficial aspects compared to the conventional arc welding process and therefore is being used as an alternative welding process. Short et al. [11] reported that the power density for laser welding is in the range of approx. 1012 W/m^2, whereas, it is approx. 109 W/m^2 for the conventional TIG welding process. This high power density for laser welding results in high penetration in a single pass resulting in a reduced overall heat input. Therefore, the grains in the weldzone are relatively fine, hence narrower HAZ and reduced structural distortions are observed as compared to TIG welding process.

Recently, for titaninum alloy particulary in sheet form, TIG welding is one of the most widely used welding methods. A main disadvantage of TIG welding is its high heat input, and this is also the cause of resulted greater distortion and higher risk of contamination [9]. Additionally, according to Cao and Jahazi although the geometrical shape of the laser welds strongly depended on the welding speed, Nd:YAG laser welding is a suitable method for Ti6Al4V sheet [12,13].

Gao and et al. (2013) attracted attention that compared with the joints TIG welded, laser welding joints have better combination of strength and ductility [9]. Akman et al. (2009) investigated the effect of the laser welding parameters - the pulse energy, pulse duration, peak power -on the microstructure and weld penetration investigated for the Ti–6Al–4V alloy [1]. When the thickness of the plate is higher than 20 mm, joints deteriorates since it is difficult to join, and large internal stress will be generated. Huang et al. (2016) reported that the welding deformation was linearly related to the laser power imposed per unit length, therefore the increase in welding peed can reduce the plate deformation and the larger plates would have more out of plane deformations under the same welding conditions [14]. Since both pulsed fiber laser and TIG welding are frequently used for welding of titanium alloys, their comparison from the perspective of mechanical properties and strength has always remained an area of prime concern. In this work, in order to get a better understanding of the influence of the pulsed fiber laser welding and conventional welding method (tungsten inert gas -TIG) laser method on the properties of Ti6Al4V joints, Ti6Al4V sheets with a thickness of 0.8 mm were welded respectively with the pulsed fiber laser and TIG arc. While the pulsed fiber laser and TIG welding process, deformation modifications were investigated via a 3D laser scanner integrated to a portable-arm Coordinate Measurement Machine (CMM) and PC-DMIS software. In previous studies [14-17], it was mentioned that both the TIG welding and the pulsed fiber laser welding were subjected to deformation measurement analyse, but there is no sufficinet researh analysis using the CMM device performed for especially Ti6Al4V sheets. Our research using CMM device has obtained the distortion amounts of deformation. In addition microstructure changes and hardness values was analyzed in relation to deformation changes.

2. MATERIAL and METHOD

2.1. Material and Welding Conditions

Welding was carried out on Ti-6Al-4V sheet with a dimension of 165x40x0.8 mm using pulsed fiber laser and TIG welding processes. Manufacturer's chemical composition data of titanium alloy sheet is given in Table1.

Table 1. The composition of Ti6Al4V (wt %)

Material	**Ti**	**Al**	**V**	**Fe**	**Si**	**C**	**N**	**H**	**O**
Content	Bal	5.5-6.8	3.5-4.5	<0.3	<0.15	<0.1	<0.05	<0.015	<0.2

Table 2. Welding parameters for fiber laser and TIG.

Welding parameters for fiber laser.

Current (A)	Pulse duration (ms)	Pulse frequency (Hz)	Welding Speed (mm/min)	Heat input (kJ/mm)
250 A	6,5	9 Hz	150	0,4– 0,7

Welding parameters for TIG.

Current (A)	Voltage (V)	Current type (AC/DC) / Pole	Welding speed (mm/s)	Heat input (kJ/mm)
24-25	9,5-9,7	DC (-)	65 – 90,1	1,2– 1,6

The rust on the plate surface around the weld line was removed before welding. The room temperature was about 20 ◦C during experiment. The welding parameters and conditions to achieve bead-on-plate weldments for each of the welding processes are presented in Table 2. Argon gas was used for shielding a pulsed fiber laser machine used for the welding process is shown in Figure 1a, TIG machine used for the welding process is shown in Figure 1b and the laser source construction technical drawing is shown in Figure1c. The welded specimens are shown in Fig. 2(a), (b), (c), (d) and respectively.

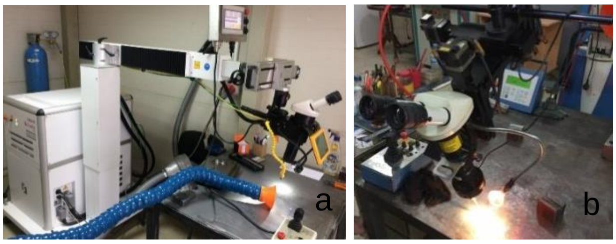

Figure 1. a) Pulsed fiber laser welding machine (Alseko-Sisma SWA 300) b) TIG welding machine (Tig-400) c) Ti-6Al-4V sheet technical drawing.

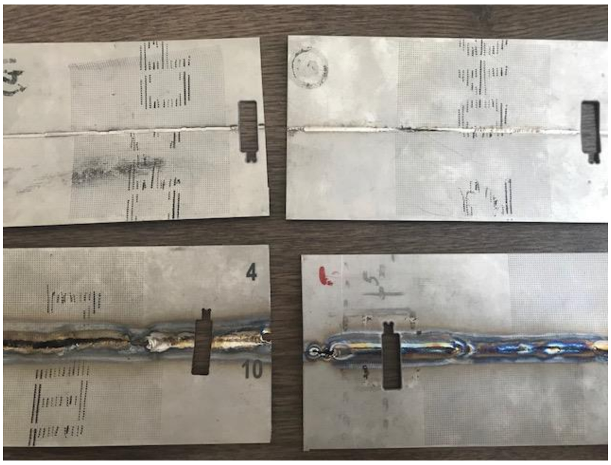

Figure 2. The welded specimens a) Pulsed fiber laser welding specimen (L1) b) Pulsed fiber laser welding specimen (L2) c) TIG welding specimen (T1) d) TIG welding specimen (T2).

2.2. Measurement of Deformation after Welding

All specimens which welded by pulsed fiber laser and TIG welding processes, have been scanned to inspect deformation amounts. HP-L.8.9 3D laser scanner integrated to Romer 7320 portable CMM and Pc-Dmis software have been used for acquiring data as point clouds. Specification of HP-L.8.9 3D laser scanner is given Table 3. CAD model of the specimens has been imported to Pc-Dmis and used as the reference for all 3D scanning operations.

After scanning of each specimen, the acquired point clouds have been aligned to CAD model to inspect deformation amounts.

Table 3. Specification of HP-L.8.9 3D laser scanner[3].

Accuracy	40 µm 2 sigma
Point acquisition rate	45 000 points per second
Points per line	750
Line rate	60 Hz
Line width (mid-field)	80 mm
Stand-off distance	135 mm +/- 45 mm
Minimum point spacing	0,08 mm
Laser power adjustment	Semi-automatic

2.3. Microstructure and Hardness

After welding, a CNC abrasive water-jet cutting machine was used to cut samples for Optical microscope (OM, Olympus DP72) and scanning electron microscope (SEM, ZEISS Sigma 300 VP) observation, respectively. Moreover, the cross- sections of the weld were prepared in order to see the shape of the molten pool and to measure the width and the depth of penetration. Metallographic samples were ground mechanically using SiC paper (250, 400, 600, 800, 1000, 2000) and polished with 1µ Struers diamond paste suspension and etched by the Kroll agent (92 ml distilled water 6 ml HNO3 and 2 ml HF) and then with 0.2%HF for metallographic study. Digital Micro-hardness Tester (Emco test DuraScan) with 100 grams in a force load under 15 s of dwell time was employed to measure the micro-hardness of the weld, HAZ, and base metal.

3. RESULTS and DISCUSSION

3.1. Comparison of Deformations and Distortions

A measurement method is needed to inspect the shape and acquire the point data of the shape. The coordinate measuring machine (CMM) is characterized with high accuracy and versatility, which has a widespread application in aerospace and manufacturing engineering. The welded sheets were scanned with a laser scanner (Hexagon) to observe the difference in deformation after welding. These Ti6Al4V sheet was welded, overlapped, In order to measure the deformation of the TIG and pulsed fiber laser source, the deviations from 9 different points were recorded using the PC-DMIS program, and deformation of the pulsed fiber laser and TIG welding was observed. Sheet which is not imposed any welding point clouds data was matched with after welding data. Figure 3 shows the comparison results of the measured points and the final section shape. TIG welding specimens (T1, T2) is given Figures 3.a and b, also Figures 3.c and 3.d show the deformation of the pulsed fiber laser welding specimens (L1, L2).

When compared distortion amounts of a specimen before and after welding both TIG welding specimens and pulsed fiber laser welding specimens, remarkable distortion has been observed after welding. However, the distortion generated by fiber laser welding is much smaller as compared to TIG welding for a 0,8 mm thick Ti6Al4V plate.

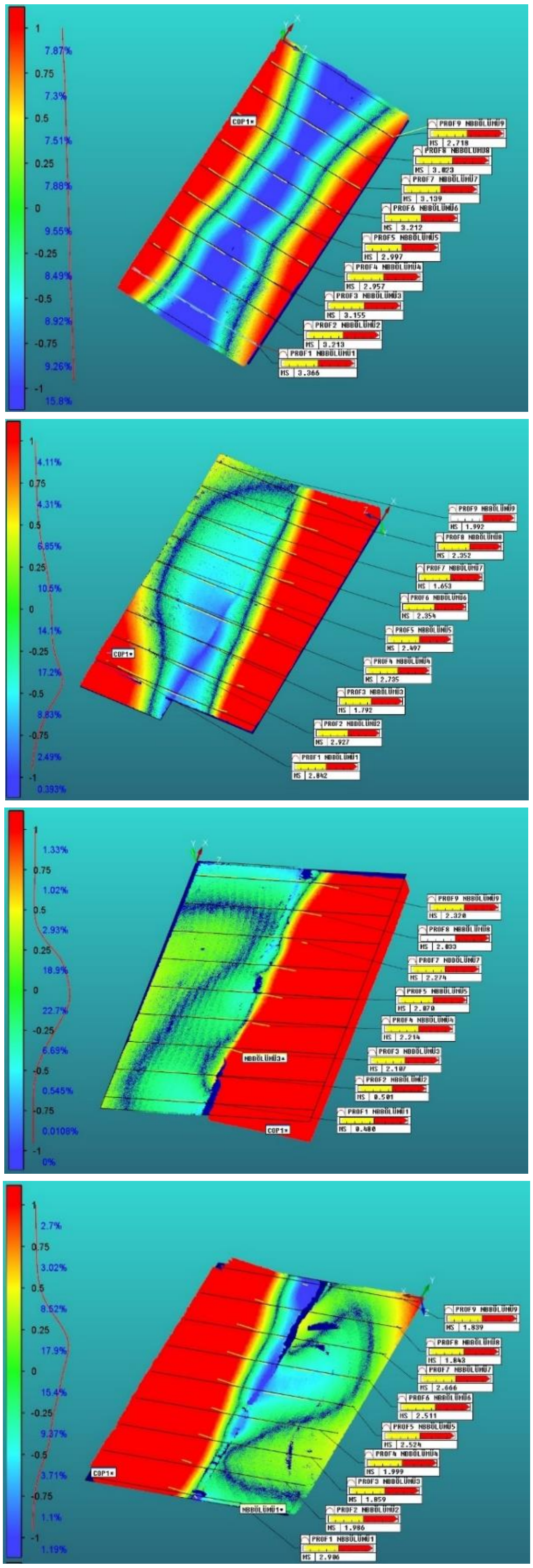

Figure 3. Cad model, point cloud (COP-Cloud of Point) and sections. a) TIG welding specimen (T1) b) TIG welding specimen (T2) c)Pulsed fiber laser welding specimen (L1) d) Pulsed fiber laser welding specimen (L2).

It can easily detect that distortion amounts of Figures 3 (a,b) are higher than Figures 3(c,d). The distortions in red and dark blue regions showed in the Figure 3 are higher and in the green regions are lower. The results of the other scanned point clouds are similar. Beside the whole point cloud comparison inspection, sections have been created in Pc-Dmis and max. deviation amount of point clouds in the sections have been measured. The values have been given in Table 4 for after welding. As shown in Figure 3.a, it can be seen that; 15.8% in the point cloud between -1 and -1.25 in the negative deviation, 7.87% in the point between 0.75 and 1 in the positive deviation. On the other hand, in Figure 3.c, maximum deviation amount of point clouds is more in the region near 0 and the point cloud densities are less in the positive and negative direction deviations. As expected, pulsed fiber laser welding specimens (L1, L2) showed the minimum distortion in comparison to the TIG welding processes because of the lower heat input and consequently narrower HAZ.

Whereas TIG welding specimens (T1, T2) showed the maximum distortion because of the higher heat input that resulted in a wider HAZ. The results by the CMM measurement and their associated measured ones are presented in Table 4.

3.2. Microstructural Evolution

Figure 4.e shows the typical microstructure of base Ti6Al4V plate. The alloy consists of equiaxed grains in prior matrix as shown in Figure 4.e. Microstructures of different zones (FZ, HAZ and PM) of pulsed fiber laser and TIG weldings are shown in Figures. 4.a, b and 4.c, respectively. Also, the welded joint of pulsed fiber laser and TIG weldings (2000X) are shown in was observed by secondary electron microscope (SEM) in Figure 4d and 4.f, respectively.

TIG welding achieves a power density of 102-104 W / cm2, while the laser beam provides a power density of 106-108 W / cm2 at the focal point. In addition, gas tungsten arc welds are low in cooling rates, generally 100–101 K / s, while laser welds have heating and cooling at very high rates, such as 105 K / s. Low heat input in laser welding, fast heating and cooling rates, more control over grain size in welding joints [18-20]. The fused zone of pulsed fiber laser weldment consists of very fine αı martensite as shown in Figure 4(f). This is due to low heat input and relatively higher cooling rate in fused zone of pulsed fiber laser as compared to fused zone of TIG weldment. Owing to the dense nature of heat source of pulsed fiber laser welding, the top and bottom width of HAZ was significantly less than that of TIG weldments (Figure 2). This is predicted to develop due to the small focal diameter of the laser source and higher cooling rate properties due to the high speed and low heat input, as mentioned in the literature [18-20]. It is also recognizable that the HAZ becomes narrower with decreasing heat input (Table 2, Figure 2).

Table 4. Maximum deviations in section after welding of samples.

Samples	**Max. Deviations in Sections (%) (After Welding)**								
Sections	**Section 1**	**Section 2**	**Section 3**	**Section 4**	**Section 5**	**Section 6**	**Section 7**	**Section 8**	**Section 9**
T1	3.366	3.213	3.155	2.957	2.997	3.212	3.139	3.023	2.718
T2	2.842	2.927	1.792	2.735	2.497	2.354	1.653	2.352	1.992
L1	0.480	0.501	2.107	2.214	2.070	2.271	2.274	2.033	2.320
L2	2.906	1.986	1.859	1.999	2.524	2.511	2.666	1.843	1.839

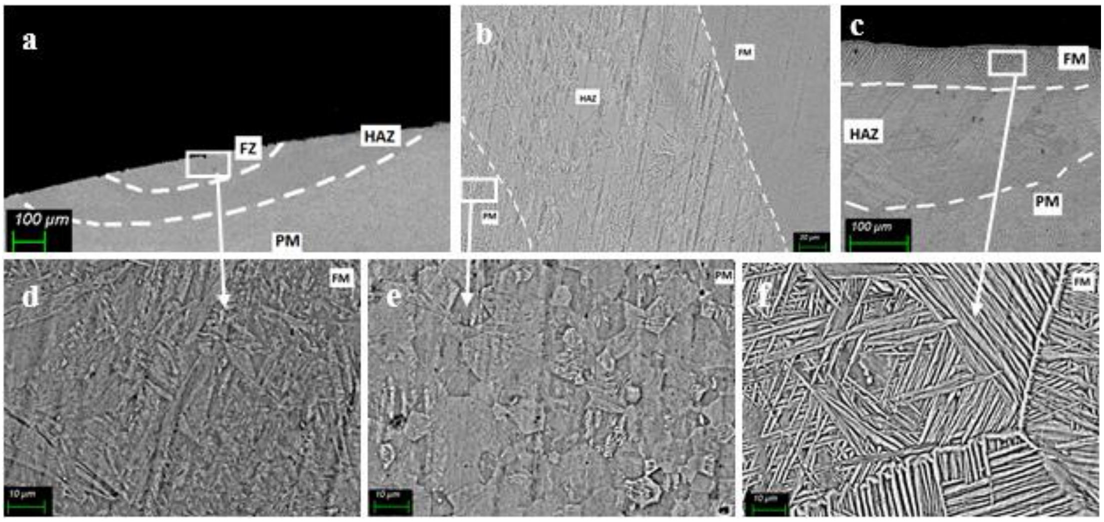

Figure 4. (a) TIG welding specimen with different zone (250X) (b) TIG welding specimen with different zone (1000X) (c) Pulsed fiber laser welding specimen with different zone (250X) (d) TIG welding specimen fused zone (e) TIG welding specimen based zone (f) Pulsed fiber laser welding specimen fused zone

3.3. Microhardness Evolution

The vickers hardness tests were applied to all welded samples to determine the hardness change in the weld zone (PM, HAZ and FZ) in titanium materials were joint with pulsed fiber laser and TIG weldments by two different sources.

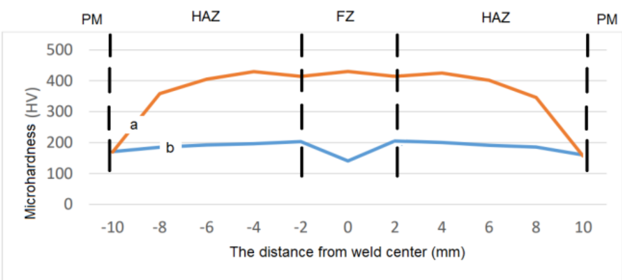

Figure 5. Vickers microhardness distribution on the cross-section of a) pulsed fiber laser and b) TIG welded joints.

Figure 5 shows the vickers microhardness distribution on the cross section of the pulsed fiber laser and TIG welded joint. When the hardness graphs are examined; it is seen that there is a drastic decrease from the FZ to PM for pulsed fiber laser welding. The highest hardness values are measured from the FZ, followed by the HAZ and PM in the pulsed fiber laser.

When the hardness results obtained are examined, the region affected by the source is wider because the heat input is higher in the TIG welding than in the laser source, and the hardness values of the substrate and the welding region of the TIG welding samples are lower than those of the laser welding. The extent of martensitic transformation gives an estimate of the microhardness of the FZ since martensite is much harder than acicular and equiaxed phase. Due to higher proportion of martensite (Figure 4.c, 4.f), the measured values of microhardness in the FZ of laser weldments was on more than that of TIG weldments. As the cooling rate increases, finer microstructures are produced. Note that high cooling rate results in much closer spacing between cellular or dendrite arms. Eventually, the finer microstructure leads to increased mechanical properties. As shown in Figure 5, the FZ in the pulsed fiber laser welded joint exhibits the highest hardness due to the formation of the αı martensite, then the hardness values drop rapidly in the HAZ of pulsed fiber laser. The microhardness in the fusion zone of TIG welded joint is much lower than that of BM in Figure 5. The reason may be the low strength-index filler wire used in the TIG welding process.

The fiber laser welding is much more mechanically favorable for Ti6Al4V sheet because of high heat input and high cooling rate causing extreme hardness and brittleness in the material.

4. CONCLUSION

Deformation pattern, residual distortions, weld geometry, microstructure and microhardness properties of the joints produced with fiber laser source and tungsten inert gas welding were compared. Considering all results, the following can be said:

- It is easily possible to detect the distortion amounts with 3D laser scanner after welding. 3D laser scanners and quality control software are useful in order to control the appropriateness of the welding parameters. When compared distortion amounts of a specimen before and after welding both TIG and pulsed fiber laser welding specimens, remarkable distortion has been observed after welding. However, the distortion generated by fiber laser welding is much smaller as compared to TIG welding for a 0,8 mm thick Ti6Al4V plate. It can be easily observed that distortion amounts of Figures 3 (a,b) are higher than Figures 3(c,d). The distortions in red and dark blue regions showed in the Figure 3 are higher and in the green regions are lower.
- The heat applied during welding is absorbed by the fusion zone and the heat affected zone. However, the effect on the microstructure is less than that of the fused zone because the heat affected zone temperature is lower than the fused zone. The fused zone in the pulsed fiber laser welding also shows the presence of needle-like αı martensite in along with acicular within the equiaxed grains in Figure 4(f). This confirms that diffusion less transformation of to αı martensite has also occurred within the prior grains of FZ.
- Joining the Ti6Al4V sheet with the laser welding method is more mechanically favorable because of low heat input and high cooling rate can cause extreme hardness and brittleness in the material.

DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

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