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TIG WELDING OF Ti6Al4V: EFFECT OF Ti6Al4V ELI AS FILLER METAL

Titanium and its alloys have significant uses in the biomedical, chemical, and aerospace industries. In this article, the current and gas flow rates were varied using Taguchi's experiment design. The mechanical properties of the welded joint made using tungsten inert gas (TIG) welding and Ti6Al4V ELI as filler metal was characterized using the microstructure, microhardness, and tensile strength. The joint was classified into three regions, namely, fusion zone (FZ), heat affected zone (HAZ), and base metal (BM). Results show martensitic microstructure within the fusion zone (FZ) and the heat affected zone (HAZ), which resulted in an increased hardness within the fusion and heat affected zone.

Keywords: Fusion welding; Microhardness; Tensile strength; Ti6Al4V; TIG

1. Introduction

Titanium alloy grade 5 (Ti6Al4V) and titanium alloy grade 23 (Ti6Al4V ELI) have been tremendously used in various industries, especially in the biomedical sector [1-4]. Bone implants have been made of Ti6Al4V ELI and Ti6Al4V due to the material's high corrosion resistance and its shear strength [5-7]. Several fusion welding techniques, such as laser welding, metal inert gas welding, and tungsten inert gas welding, have been commonly used in joining Ti6Al4V [8-10]. However, tungsten inert gas (TIG) provides a good joining strength and is relatively economical compared to other techniques [11]. Despite the excellent joining techniques, one of the limitations of Ti6Al4V is the oxidation of the material at a temperature of 350°C and above [12,13]. The oxidation results in contamination of the weld, resulting in reduced material mechanical strength [14].

Several authors have researched the joining of Ti6Al4V using TIG welding. Optimizing the parameters to achieve a good mechanical strength has also been carried out. Among the optimization techniques used in TIG welding is Weibull distribution [15], Taguchi [16], artificial neural network [17,18], and other hybrid optimization techniques [7,19]. Results have shown that welding current, gas flow, and welding speed are germane to achieving a good weld. In their study, Reda et al., [20] found current to play a significant role in influencing the microstructure of Ti6Al4V alloy. An increase in current was reported to create a coarse grain within the microstructure, consequently reducing the material's tensile strength and increasing the material's hardness. A similar study by Gope et al., [20] also shows that the fusion zone's martensitic microstructure is responsible for increased hardness.

In a study by Iitaf et al., [21], the use of filler metals such as Ti6Al4V and Ti5Al2.5Sn shows the presence of an increased α' martensitic formation within the fusion zone of the weld. When Ti6Al4V was used as filler material as compared to the Ti5Al2.5Sn as a result of the increased amount of β stabilizer in Ti6Al4V the hardness of the weld increases when compared to samples welded using Ti5Al2.5Sn and that welded autogenously.

Hoye et al., [13] studied the effect of shielding gas on the physical and mechanical properties of Ti6Al4V. Results show that gas flow significantly impacts the level of contamination of welds with the presence of interstitial species detected in the weld. Insufficient gas shielding was also observed to affect the coloration of welds, where blue-colored beads were observed. Furthermore, the weld contamination also increases hardness within the weld. Porosity is also a defect resulting from insufficient

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gas shielding during TIG welding [21]. The use of filler metals will mitigate the defects that occur during welding.

Even though the use of TIG technology to weld Ti6Al4V has been extensively reported, the scope that still needs to be understood is still broad, as the effect of the use of the extra low interstitial (ELI) version of Ti6Al4V as filler metal during the TIG welding of Ti6Al4V sheets, viz-a-viz the effect of the extra oxygen in the ELI version has not been adequately discussed. Therefore, this article investigates the mechanical and microstructural properties of TIG-welded Ti6Al4V sheets using Ti6Al4V ELI as filler metal.

2. Materials and methods

Mill annealed Ti6Al4V sheets with a chemical composition of 6.10% aluminum, 4% vanadium, 0.15% iron, 0.13% oxygen, and the rest being titanium, with a dimension of 100×60×2 mm, were joined using an Afrox industrial 175 multiprocess welding machine. The faying sides were cleaned using acetone to remove impurities prior to welding. A gap of 1mm was left between the faying surfaces to accommodate the filler metal, which is a 1.6 mm thick Ti6Al4V extra low interstitial (ELI) with a chemical composition of 6.14% aluminum, 4.15% vanadium, 0.10% oxygen, 0.125% iron and the remainder being titanium. Pure argon gas of 99% purity was used as the shielding gas, with a provision of back purging. The Ti6Al4V sheets were joined in the butt configuration. Fig. 1 shows the schematics of the experimental setup. The experiment design used is that of Omoniyi et al., [1], which is presented in TABLE 1. The data used for the microhardness and the tensile strength are adapted from the open-source data article of Omoniyi et al., [1].

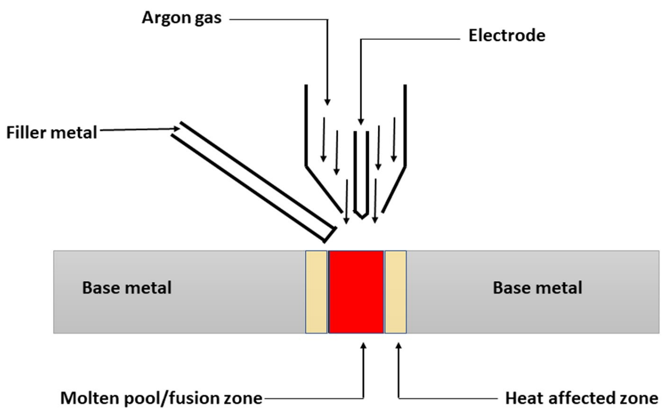

Fig. 1. Schematics of the experimental setup

TABLE 1

Process Parameters for TIG welding experiment [1]

Sample No.	Current (A)	Gas Flow Rate (L/min)
T21	60	9
T22	50	9
T23	50	7
T24	60	7

Three samples were cut out across the metal according to the ASTM E8 [22] for tensile tests. The tensile test was carried out on a UTM Zwick Roell 2250. Another sample was cut across the weld measuring 25×10 mm for microstructure characterization. The 25×10 mm sample was mounted on an epoxy resin, then grinded using silicon carbide papers ranging from #320-1200 before they were polished and etched using Kroll's reagent. The microstructure images were captured at the base metal (BM), heat affected zone (HAZ), and fusion zone (FZ). The microhardness of the sample was conducted using a force of 4.9 N and a dwell period of 15 s. Phases identification was carried out using the X-ray diffraction (XRD) analysis.

3. Results and discussion

3.1. Microstructure

Welding involves the application of heat to melt metal, which means the metal to be joined attains the liquidus temperature before cooling [23]. The weld region is characterized by the fusion zone (FZ), which is the portion that attains the highest temperature, the heat affected zone (HAZ), which is close to the FZ but attains a temperature lower than that of the FZ, and the base metal (BM) which is also the parent metal [8,10], as shown in Figs. 2-5. The microstructure of the Ti6Al4V and Ti6Al4V ELI is made of the alpha (α) and the beta (β) phases at room temperature [3,24]. At the β transus temperature of Ti6Al4V (995°C), the phases transform [5]. However, the temperature attained in HAZ is said to be around the β transus temperature or higher but lower than the liquidus temperature, even if the boundary between the HAZ and FZ can sometimes be challenging to determine. The FZ of all the samples is characterized by the columnar β grains with an average grain size of approximately 500 μm [17,24]. This large size of prior β grain results from rapid cooling resulting in martensitic microstructure formation [20]. A similar phenomenon is also observed within the HAZ [25]. The average grain size within the HAZ is 560 μm, while that of the base metal is approximately 13 μm, similar to the observations of [26,27].

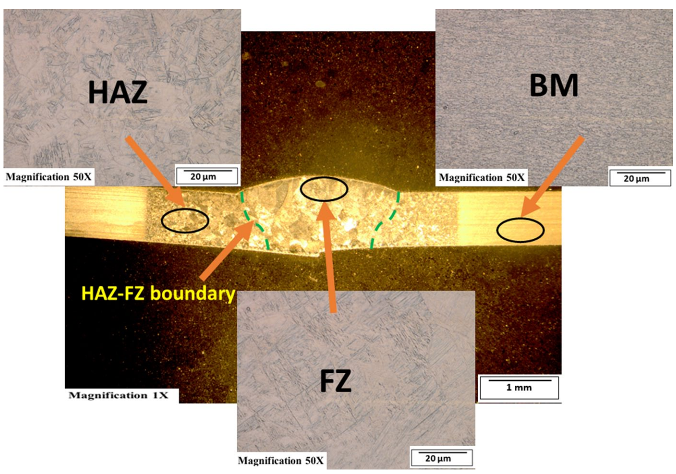

Fig. 2. Microstructure of sample T21 showing the three weld regions

The large sizes of the prior β have been reported to reduce the mechanical strength of Ti6Al4V. Generally, when the microstructure of the samples was compared with that of Omoniyi et al., [12], which were welded autogenously, the material exhibited the same microstructural transformation, which could be due to the huge similarities between the Ti6Al4V ELI and Ti6Al4V.

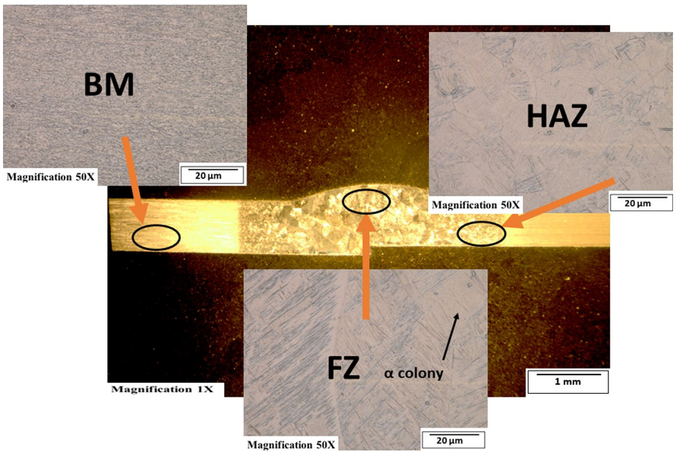

Fig. 3. Microstructure of sample T22 showing the three weld regions

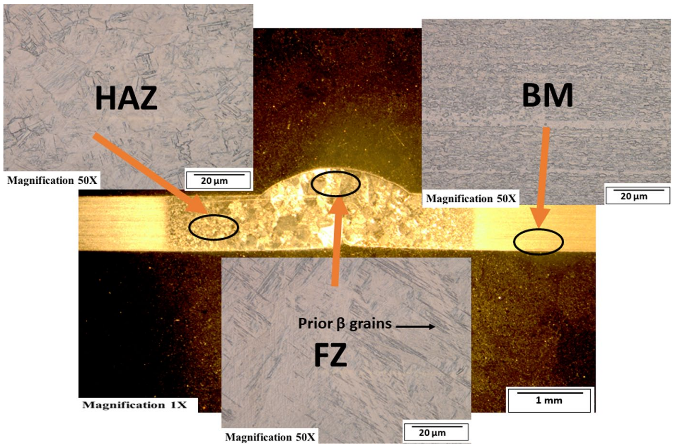

Fig. 4. Microstructure of sample T23 showing the three weld regions

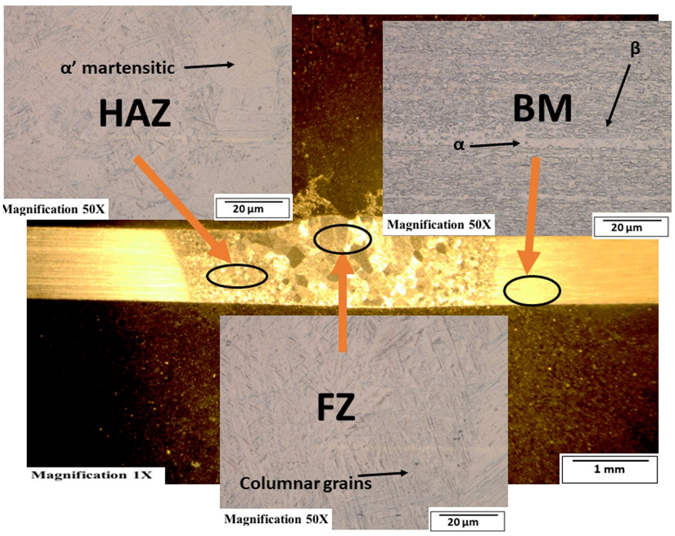

Fig. 5. Microstructure of sample T24 showing the three weld regions

3.2. Tensile Strength

The tensile strength and corresponding elongation of each sample are presented in Fig. 6. The material's ductility is generally observed to have increased due to the Ti6Al4V ELI present within the FZ [11]. Ductility is also improved due to a decrease in slip length with cooling rate and the size of the α colony [26]. The reduced tensile strength in samples T21, T22, and T23 could be attributed to the large size prior β microstructure within the FZ [28,29], and as a result, all these samples failed within the FZ. Sample T24 failed at the HAZ.

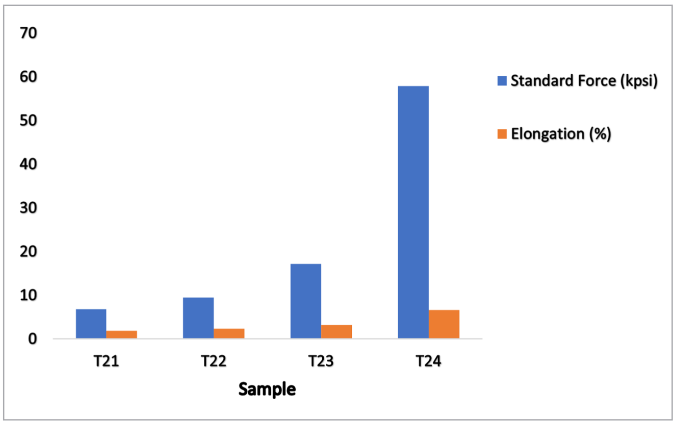

Fig. 6. Tensile strength and percentage elongation of welded samples

3.3. Hardness

The microhardness across the weld shown in Fig. 7 increases across the FZ, with the average hardness across the HAZ being slightly lower than that of the BM. The FZ has the highest hardness level ranging from 362.7-381.3 HV as a result of the α' martensitic microstructure formed during the cooling process of the melt pool. According to Omoniyi et al., [8,10], melt pool cooling above the critical cooling rate of 410°C/s results in

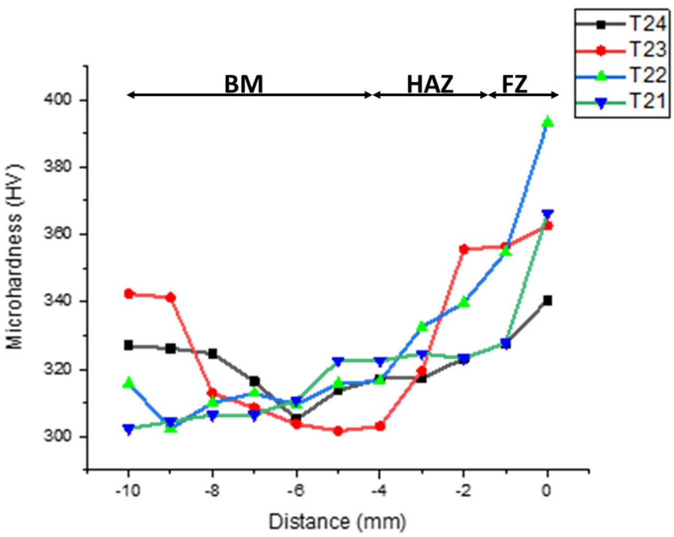

Fig. 7. Microhardness profile of welded samples

α' martensitic microstructure, resulting in high hardness [30]. The slightly higher oxygen content in the ELI version of Ti6Al4V further contributed to the increase of hardness within the FZ. The average hardness with the HAZ ranges from 342.1-370 HV, while that of the BM ranges from 342.1-376.2 HV. Similar observations are reported in [31].

3.4. X-Ray Diffraction (XRD) Analysis

Fig. 8 shows the XRD of the base material and the welded section for each sample. The base metal material shows the material is made of the *α* and *β* phases as also observed by Kumar et al., [25]. Yet, the welded samples show no difference in phase transformation irrespective of the welding current and gas flow rate. The higher presence of *α* phase further confirm the transformation of $\beta \rightarrow \alpha$ phase and the transition of *α* to *α*' martensitic microstructure at the fusion zone.

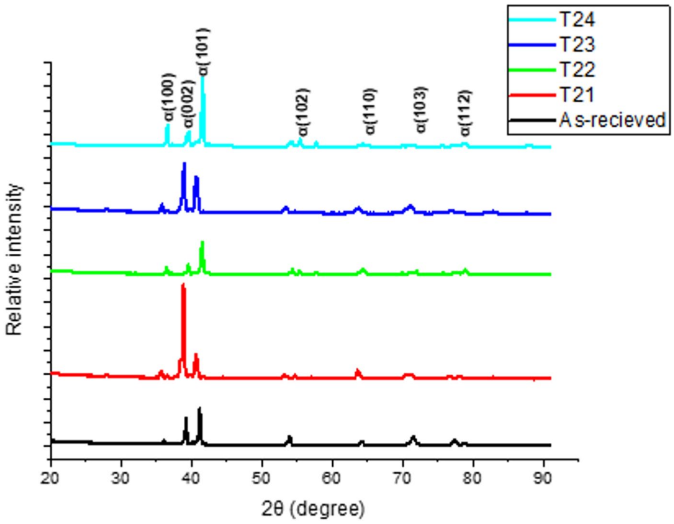

Fig. 8. XRD pattern of the as-received sample and the welded samples

4. Conclusion

The article has investigated the effect of Ti6Al4V ELI as a filler metal on TIG welding of Ti6Al4V. Four welds were carried out by varying the input current and gas flow rate. Furthermore, the welds were characterized by tensile, microhardness, and microstructure. The following conclusions are drawn from the experiment.

1. The microhardness is highest at the FZ due to the martensitic microstructure formed within the zone and the presence of more oxygen introduced through the filler metal.
2. The microstructure of the samples is generally characterized at the FZ and HAZ by martensitic microstructure, with the BM having an equiaxed *α* and *β* phases.
3. It is concluded that using filler metal such as Ti6Al4V ELI is feasible for joining Ti6Al4V sheets without introducing new phases or intermetallics.

Conflict of Interest

None declared.

REFERENCES

[1] P. Omoniyi, M. Mahamood, T. Jen, E. Akinlabi, TIG welding of Ti6Al4V alloy: Microstructure, fractography, tensile and microhardness data, Data Br. **38**, 107274 (2021). DOI: https://doi.org/10.1016/j.dib.2021.107274

[2] P.O. Omoniyi, E.T. Akinlabi, R.M. Mahamood, T.C. Jen, Corrosion Resistance of Heat Treated Ti6Al4V in NaCl, Chem. Data Collect. (2021). DOI: https://doi.org/10.1016/j.cdc.2021.100780

[3] P.O. Omoniyi, E.T. Akinlabi, R.M. Mahamood, Microstructural and Mechanical Properties of Laser Deposited Ti-6Al-4V Alloy: A Review, in: 4th Int. Conf. Eng. a Sustain. World, (2021). DOI: https://doi.org/10.1088/1757-899X/1107/1/012110

[4] S. Dewangan, R. Ranjan, S. Chattopadhyaya, Preliminary Investigations of Structure and Properties of TIG Welded Ti-6Al-4V Alloy, Adv. Sci. Technol. Res. J. **15**, 156-165 (2021).

[5] P.O. Omoniyi, R.M. Mahamood, N. Arthur, S. Pityana, S.A. Akinlabi, Y. Okamoto, M.R. Maina, E.T. Akinlabi, Investigation and optimization of heat treatment process on tensile behaviour of Ti6Al4V alloy, Mater. Werkstofftech. **52**, 1057-1063 (2021). DOI: https://doi.org/10.1002/mawe.202000314

[6] P.O. Omoniyi, E.T. Akinlabi, R.M. Mahamood, Heat Treatments of Ti6Al4V Alloys for Industrial Applications: An Overview, in: 4th Int. Conf. Eng. a Sustain. World, (2021). DOI: https://doi.org/10.1088/1757-899X/1107/1/012094

[7] C. Prakash, S. Singh, M. Singh, M.K. Gupta, M. Mia, A. Dhanda, Multi-objective parametric appraisal of pulsed current gas tungsten arc welding process by using hybrid optimization algorithms, Int. J. Adv. Manuf. Technol. **101**, 1107-1123 (2019). DOI: https://doi.org/10.1007/s00170-018-3017-3

[8] P.O. Omoniyi, R.M. Mahamood, N. Arthur, S. Pityana, S. Skhosane, Y. Okamoto, T. Shinonaga, M.R. Maina, T.C. Jen, E.T. Akinlabi, Joint integrity evaluation of laser beam welded additive manufactured Ti6Al4V sheets, Sci. Rep. **12**, 1-9 (2022). DOI: https://doi.org/10.1038/s41598-022-08122-2

[9] P.O. Omoniyi, R.M. Mahamood, E.T. Akinlabi, Impact of Process Parameters of Laser Welding on the Mechanical Properties of Ti6Al4V: A Review, J. Chem. Technol. Metall. **56**, 1074-1081 (2021).

[10] P. Omoniyi, R. Mahamood, N. Arthur, S. Pityana, S. Skhosane, Y. Okamoto, M. Maina, T. Jen, E. Akinlabi, Laser Butt Welding of Thin Ti6Al4V Sheets : Effects of Welding Parameters, J. Compos. Sci. **5**, 1-9 (2021). DOI: https://doi.org/10.3390/jcs5090246

[11] A.B. Short, Gas tungsten arc welding of α + β titanium alloys: A review, Mater. Sci. Technol. **25**, 309-324 (2009). DOI: https://doi.org/10.1179/174328408X389463

[12] P.O. Omoniyi, R.M. Mahamood, N. Arthur, S. Pityana, S.A. Akinlabi, S. Hassan, Y. Okamoto, M.R. Maina, E.T. Akinlabi, Investigation of the Mechanical and Microstructural Properties of TIG Welded Ti6Al4V Alloy, in: Adv. Mater. Sci. Eng. Sel. Artic. from ICMMPE 2020, pp. 111-118, (2021).

[13] N. Hoye, H. Li, J. Norrish, R. Dippenaar, Post-weld atmospheric contamination of gas tungsten arc deposited welds in commercially pure and Ti-6A1-4V titanium alloys, in: Ti 2011 – Proc. 12th World Conf. Titan., pp. 1629-1633 (2012).

[14] P.O. Omoniyi, R.M. Mahamood, T. Jen, E.T. Akinlabi, An Overview of TIG Welding of Ti6Al4V: Recent Developments, Rev. Des Compos. Des Matériaux Avancés-Journal Compos. Adv. Mater. **31**, 265-274 (2021).

[15] M. Balasubramanian, Statistical analysis of tensile strength and elongation of pulse TIG welded titanium alloy joints using Weibull distribution, Cogent Eng. **3** (2016).
DOI: https://doi.org/10.1080/23311916.2016.1239298

[16] S. Reddy Vempati, K. Brahma Raju, K. Venkata Subbaiah, Optimization of Welding Parameters of Ti 6al 4v Cruciform shape Weld joint to Improve Weld Strength Based on Taguchi Method, Mater. Today Proc. **5**, 4948-4957 (2018).
DOI: https://doi.org/10.1016/j.matpr.2017.12.072

[17] F. Karimzadeh, A. Ebnonnasir, A. Foroughi, Artificial neural network modeling for evaluating of epitaxial growth of Ti6Al4V weldment, Mater. Sci. Eng. A. **432**, 184-190 (2006).
DOI: https://doi.org/10.1016/j.msea.2006.05.141

[18] R. Kumar, S. Chattopadhyaya, S. Kumar, Prediction of bead reinforcement height and width of Gas Tungsten Arc Welded bead-on plate joints using Artificial Neural Network, in: 5th Int. 26th All India Manuf. Technol. Des. Res. Conf., Assam, pp. 1-6, (2014).

[19] V. Kalaichelvi, R. Karthikeyan, D. Sivakumar, Analysis of gas metal arc welding process using GA tuned fuzzy rule based system, J. Intell. Fuzzy Syst. **25**, 429-440 (2013).
DOI: https://doi.org/10.3233/IFS-120650

[20] D.K. Gope, U. Kumar, S. Chattopadhyaya, S. Mandal, Investigation into the TIG welded joint of titanium G-5 alloy sheet Investigation into the TIG welded joint of titanium G-5 alloy sheet, in: Int. Conf. Mech. Renew. Energy, IOP Publishing, (2018), pp. 1-8.
DOI: https://doi.org/10.1088/1757-899X/377/1/012114

[21] A. Iltaf, F.N. Khan, T. Shehbaz, Influence of filler material on the microstructure, mechanical properties, and residual stresses in tungsten inert gas welded Ti-5Al-2. 5Sn alloy joints, J. Mater. Des. Appl. 1-15 (2021).
DOI: https://doi.org/10.1177/14644207211012433

[22] ASTM E8, Standard Test Methods for Tension Testing of Metallic Materials 1, ASTM Stand. (2016).
DOI: https://doi.org/10.1520/E0008

[23] M.S. Sai, V. Dhinakaran, K.P.M. Kumar, V. Rajkumar, B. Stalin, T. Sathish, A systematic review of effect of different welding process on mechanical properties of grade 5 titanium alloy, Mater. Today Proc. **21**, 948-953 (2020).
DOI: https://doi.org/10.1016/j.matpr.2019.09.027

[24] R. Reda, M. Magdy, M. Rady, Ti – 6Al – 4V TIG Weld Analysis Using FEM Simulation and Experimental Characterization, Iran. J. Sci. Technol. Trans. Mech. Eng. (2019).
DOI: https://doi.org/10.1007/s40997-019-00287-y

[25] K. Kumar, M. Masanta, S. Kumar Sahoo, Microstructure evolution and metallurgical characteristic of bead-on-plate TIG welding of Ti-6Al-4V alloy, J. Mater. Process. Technol. **265**, 34-43 (2019).
DOI: https://doi.org/10.1016/j.jmatprotec.2018.10.002

[26] N.K. Babu, S.G.S. Raman, Influence of current pulsing on microstructure and mechanical properties of Ti-6Al-4V TIG weldments, Sci. Technol. Weld. Join. **11**, 442-447 (2006).
DOI: https://doi.org/10.1179/174329306X120750

[27] V. Vaithiyanathan, V. Balasubramanian, S. Malarvizhi, V. Petley, S. Verma, Combined Effect of Gas Tungsten Arc Welding Process Variants and Post-Weld Heat Treatment on Tensile Properties and Microstructural Characteristics of Ti–6Al–4V Alloy Joints, Metallogr. Microstruct. Anal. **9**, 194-211 (2020).
DOI: https://doi.org/10.1007/s13632-020-00631-8

[28] A. Rahimi, M. Shamanian, The PC – GTAW of Ti – 6Al – 4V Thin Sheets and Its Effects on Mechanical and Microstructural Properties, Metallogr. Microstruct. Anal. **8**, 871-879 (2019).
DOI: https://doi.org/10.1007/s13632-019-00595-4

[29] X.L. Gao, L.J. Zhang, J. Liu, J.X. Zhang, A comparative study of pulsed Nd: YAG laser welding and TIG welding of thin Ti6Al4V titanium alloy plate, Mater. Sci. Eng. A. **559**, 14-21(2013).
DOI: https://doi.org/10.1016/j.msea.2012.06.016

[30] Y. Li, J.-Y. Hou, W.-J. Zheng, Z.-Q. Wan, W.-Y. Tang, A Numerical Simulation Method Considering Solid Phase Transformation and the Experimental Verification of Ti6Al4V Titanium Alloy Sheet Welding Processes, Materials (Basel) **15**, 1-27 (2022).

[31] M. Villa, J.W. Brooks, R. Turner, R.M. Ward, Metallurgical Modelling of Ti-6Al-4V for Welding Applications, Metals (Basel) **11**, 1-20 (2021).