Determination of Optimal Weld Parameter for Joining Titanium Alloys by Gas Tungsten Arc Welding using Taguchi Method

Nazmul Huda*, Jae Won Kim**, Changwook Ji**, Dae-Geun Nam*** and Yeong-Do Park****,†

*Department of Mechanical and Mechatronics Engineering, University of Waterloo,
Waterloo, Ontario, N2L 3G1, Canada

**Advanced Forming Process R&D Group, Korea Institute of Industrial Technology, Ulsan, 44776, Korea

***Dongnam Division, Korea Institute of Industrial Technology, Busan, 46938, Korea

****Dong-Eui University, Department of Advanced Material Engineering, Busan, 47340, Korea

†Corresponding author: ypark@deu.ac.kr

(Received December 6, 2020; Revised December 17, 2020; Accepted January 22, 2021)

Abstract

The optimal parameters for joining two different titanium alloys were determined by the Taguchi method and applied in similar and dissimilar joining of conventional Ti-6Al-4V and newly developed Ti-3Al-2.5V alloys. The microstructures of the two alloys and their mechanical properties were comparatively evaluated at the optimal parameters. The Ti-6Al-4V alloy showed a larger back bead width than that of Ti-3Al-2.5V under similar heat input, because of its lower thermal conductivity and higher specific heat capacity. The welded zone of Ti-3Al-2.5V contained a retained beta phase, which was absent in that of Ti-6Al-4V. This indicates that the transformation of the Ti-3Al-2.5V weld metal starts above the martensite temperature, while it starts below the martensite temperature for Ti-6Al-4V. The failure of the welded specimen occurred in the base metal for both the titanium alloys, which indicates the superior weld quality. However, the welded Ti-6Al-4V showed superior tensile strength to that of the Ti-3Al-2.5V weld under optimal conditions, owing the high beta phase fraction in its base metal. Meanwhile, it showed inferior ductility to that of Ti-3Al-2.5V because of its coarser beta phase.

Key Words: Titanium alloys, Taguchi method, Optimal parameters, Microstructure, Mechanical properties

1. Introduction

Gas tungsten arc (GTA) welding is a favorable welding process for titanium alloys, especially for thin titanium sheets. GTA welding can successfully avoid/reduce the contamination of titanium and potential property degradation by providing a proper shielding environment. The macro attributes of weldments such as defects, bead geometry, penetration, and hardness distribution across the weld zone to heat affected zone are essential entities in determining the weldability of a material. In an arc welding process, these factors are influenced by the material properties such as chemical composition, thermal conductivity, melting point, reactivity, and welding process parameters such as welding current, arc length,

welding speed, shielding gas. The bead geometry can profoundly influence the mechanical properties of the welds, especially with thin sheets. Earlier, the effect of welding parameters on weld geometry was studied with GTA welding of stainless steel¹⁾ and laser welding of Ti-6Al-4V²⁾. Generally, different standards from handbooks or research articles are used to find out the desired welding process parameter. However, it does not always ensure proper bead geometry. The benefits of using linear regression modeling, statistical experimental design, and neural networks to investigate the effect of welding process parameters on the weld bead geometry have been reported by several studies^{3,4)}.

Taguchi method was employed to find out the optimal parameters for the welding of titanium by several authors. However, most of these works terminated after

finding suitable welding parameters without evaluating the microstructure and mechanical properties with the optimal welding conditions. Therefore, this research focuses on determining the optimal GTA welding parameters for two titanium alloys by the Taguchi method and the experimental validation. Also, the microstructure and mechanical properties of the welds with optimal process conditions are evaluated, and a comparison is made between the two alloys.

2. Design of experiment in taguchi method

Taguchi method is a powerful tool that helps to improve the performance of the product quality, process, design, and system with minimum experiments, time, and cost. The methodology of Taguchi helps to find out the optimal settings of control factors. First, it is necessary to find out the main control parameters which influence the quality of the product. Secondly, the orthogonal array from the design of Taguchi is chosen based on the number of factors and their level. The experiments are carried out as the designed orthogonal array. Thirdly, orthogonal array and experimental data tables are set out for analysis. The best level of control parameters for the quality of output is determined after some analysis. Finally, the optimized parameters are verified through experimentation.

The most influencing parameters which might affect the bead geometry in TIG welding of titanium are weld current, welding speed, arc length, shielding gas flow rate, electrode tip, etc. Nevertheless, choosing too many parameters or a small number of factors to varying for Taguchi analysis might cause a negative effect in weld qualities⁵⁾. In this study, the three most influencing factors, such as weld current, welding speed, and arc length, are considered, with each having three levels. After performing some experiments, the maximum and minimum level of each parameter is determined, which is shown in Table 1. Level 1 in Table 1 represents the minimum value, while level 3 is the maximum. An intermediate of level 2 is chosen randomly. The bead acceptance criterion is chosen based on the back bead width. The proper, intensive, and extensive bead criteria are defined according to Table 2⁶⁾

Table 1 Arc length, welding current, and welding speed limiting range for experiments

Symbol	Welding parameter	Level1	Level2	Level3
A	Arc length, mm	0.5	1.0	1.5
B	Welding current, A	60	70	80
C	Welding speed, mm/min	225	300	375

Table 2 Bead acceptance criteria for a particular combination of experimental parameters

Back bead width	Bead conditions
$1 \text{ mm} < B$	Intensive bead
$1 \text{ mm} < B < 3 \text{ mm}$	Proper bead
$B > 3 \text{ mm}$	Extensive bead

Fig. 1 GTA welding set up with trailing and back shielding for titanium alloys

3. Materials and method

Ti-6Al-4V and Ti-3Al-2.5V specimens of 1.0 mm thickness with a 150 mm × 50 mm dimension were used for welding. Autogenous GTA welds (BOP-Bead on Plate) were made on sheets with direct current pulsing by GTA power source (water-cooled) with polarity DCEN (Direct Current Electrode Negative). The experimental set up is shown in Fig. 1. The electrode for welding was 2% thoriated tungsten with a diameter of 1.6 mm. A gas cup of 19 mm diameter and a gas lens were used for the uniform and non-turbulent gas flow to the weld pool. The argon gas with a purity of 99.995 % was used for primary and secondary back shielding was also applied to prevent excessive oxidation during the welding process. A trailing shielding (secondary shielding) was attached to a gas nozzle with shielding face dimensions 70 mm × 35 mm. Before welding, the sheet surface was cleaned by acetone and then pickled with a solution of 4 % hydrofluoric acid (concentration: 52 %) and 35 % nitric acids (concentration: 70 %) in distilled water. A thickness gauge was used to measure the arc length, and an arc welding wave analyzer measured the voltage. The average voltage corresponding to 0.5 mm, 1.0 mm, and 1.5 mm arc length was measured as 8.83 V, 9.20 V, and 9.5 V, respectively. The bead width measurement was done in a stereomicroscope and microstructure observed in Olympus BX 51M. The microstructure was revealed by chemical etching with a solution of 10 mL HF, and 25 mL HNO₃ in 100 mL of distilled water for 30 s.

4. Results and discussion

4.1 Optimal Parameters Determination

In this study, an L_9 orthogonal array is chosen to find the effect of each parameter level with quality characteristics chosen by Taguchi nominal is the best signal to noise ratio $[10 \log(Y_{\text{bar}}^2/s^2)]$. However, the interaction effect of the welding parameters is not taken into account in the present study. The experiment is carried out according to the orthogonal array. The weld surface bead width and back bead width for Ti-6Al-4V and Ti-3Al-2.5V sheets with the signal to noise (S/N) ratio from Taguchi analysis are shown in Table 3. In experiment number 5, there is no back bead observed in Ti-3Al-2.5V, but proper back bead width ($1 \text{ mm} < B < 3 \text{ mm}$) is obtained in Ti-6Al-4V. For experiment number 9, the back bead width for Ti-6Al-4V is extensive, while it is the proper bead for Ti-3Al-2.5V. In the case of the experiment with high heat input like experiment number 6, this difference in back bead width between the alloys become more prominent. The back bead width obtained for Ti-6Al-4V is wider than that of the Ti-3Al-2.5V for most of the experiment, which is shown in Fig. 2. Therefore, it can be concluded that Ti-6Al-4V has a wider back bead width compared to Ti-3Al-2.5V for the same welding conditions. The reason for this behavior can be explained by the thermal properties of the two alloys. The thermal properties are summarized in Table 4. Ti-3Al-2.5V possesses higher thermal conductivity and low heat capacity than the counterpart⁷⁾. Higher thermal conductivity enhances the heat dissipation in Ti-3Al-2.5V and thereby less heat concentration compared to Ti-6Al-4V during welding. These results in the formation of low back bead width in Ti-3Al-2.5V compared to Ti-6Al-4V.

Fig. 2 Back bead width comparison between two alloys at different heat input (solid line for Ti-6Al-4V and dot line for Ti-3Al-2.5V)

Table 4 Thermal properties of titanium alloys used in this study

Materials	Thermal conductivity (W/m · K)	Specific heat capacity (J/g · C)
Ti-6Al-4V	6.7	0.5263
Ti-3Al-2.5V	8.3	0.5250

Since the experimental design is orthogonal, the effect of each welding parameter at different levels by the Taguchi method can separate output results. For example, the mean of S/N ratio of the arc gap levels 1, 2, and 3 can be calculated by averaging the signal to noise ratio of experiments 1 to 9. The mean S/N ratio of each level of the welding process parameters is called multi repose signal to noise ratio⁸⁾, which is shown in Table 5. With a more significant difference (Δ) between the maximum S/N and the minimum S/N ratio, the effect of the parameter on the process will be larger. From Table

Table 3 Surface and back bead width of Ti-6Al-4V and Ti-3Al-2.5V and S/N ratio

Experiment no	Arc length (A)	Welding current (B)	Welding speed (C)	Heat input (J /mm)	Ti-6Al-4V			Ti-3Al-2.5V		
					Surface bead width (mm)	Back bead width (mm)	S/N ratio (db)	Surface bead width (mm)	Back bead width (mm)	S/N ratio (db)
1	1	1	1	141	4.21	2.46	8.61	3.62	1.87	6.92
2	1	2	2	123	4.13	2.25	7.60	4.32	2.78	10.26
3	1	3	3	113	4.38	2.65	9.17	4.05	2.00	6.38
4	2	1	2	110	2.91	0.00	-3.01	3.03	0.00	-3.01
5	2	2	3	103	3.51	1.11	2.68	3.15	0.00	-3.01
6	2	3	1	196	6.89	6.46	26.83	6.42	4.69	13.14
7	3	1	3	91	1.74	0.00	-3.01	2.80	0.00	-3.01
8	3	2	1	177	5.09	3.70	13.00	4.97	3.48	12.06
9	3	3	2	152	4.33	3.36	14.97	4.33	2.44	8.07

5, it is confirmed that the most influencing parameter for the welding of Ti-6Al-4V is welding current (Rank 1) whereas, for Ti-3Al-2.5V, it is welding speed (Rank 1). This could be another reason for the wider back bead width of Ti-6Al-4V as the bead width increases with weld current and decreases with welding speed. Though the weld current and welding speed are having a significant effect on the bead geometry of these titanium alloys, arc length shows trivial impact as suggested by the maximum and minimum S/N ratio difference (Δ).

Generally, parameter combination with a larger S/N ratio is consistent with better quality characteristics. However, the relative importance among the welding process parameters combination must still be known so that the optimal combinations of welding process parameters level can be determined more accurately⁽⁸⁾. Taking a higher S/N ratio into considerations, from Table 5 the optimal parameter comes A2B3C1 (1.0 mm arc length, weld current 80 A, welding speed 225 mm/min) for Ti-6Al-4V alloy. However, from Table 3, it can be seen that for Ti-6Al-4V alloy at experiment 6 with A2B3C1 parameters combination (arc length 1.0 mm, weld current 80 A and welding speed 225 mm/min) the back bead width exceed way above 3 mm range. Taking a higher S/N ratio into considerations; for Ti-3Al-2.5V, the optimum parameter is A1B3C1 (Table 5). Nevertheless, Table 3 suggests, at A2B3C1 (experiment 6) parameter combination, the back bead width is above 3 mm. Choosing A1B3C1 (only change in arc length, which has little effect compared to A2B3C1) might not make the back bead below 3mm for Ti-3Al-2.5V. So, neither of the alloys could have a proper back bead choosing the larger S/N ratio characteristics. So, it is chosen to use the parameters which have a medium value of S/N ratio. So, from Table 5, the optimal parameters are chosen as A3B2C2 (arc length 1.5 mm, weld current 70 A and welding speed 300 mm/min) for both alloys.

4.2 Verification by Experiments

Proper bead geometry is characterized by intermediate back bead width with full penetration. Neither too large

Table 6 Bead width of surface and backside with optimal welding conditions

Materials	Bead width, mm	
	Surface	Back
Ti-6Al-4V	3.87	1.72
Ti-3Al-2.5V	3.79	1.66

nor too low bead width is expected as it could affect the weld strength. The experiment is carried out for both titanium alloys at optimum conditions A3B2C2 (arc length 1.5mm, weld current 70 A and welding speed 300 mm/min), and the results are shown in Table 6. The back bead width of the alloys obtained is reasonable (within 1 mm < B < 3 mm) for both alloys. Therefore, the Taguchi method can properly optimize bead geometry. Also, it is worthwhile to notice that Ti-6Al-4V shows a wider back bead width than Ti-3Al-2.5V at optimum welding conditions.

4.3 Comparison of surface bead width and back bead width at a different heat input

All the possible 27 combinations of parameters is used to investigate the difference of surface and back bead width between these two alloys. The measurement results of bead width fo produced BOP on two titanium alloys are shown in Fig. 3. In most of the heat input (Heat input, $Q = A \cdot V \cdot 60/S$; where A = weld current, V = voltage, S = welding speed) Ti-6Al-4V possesses a wider surface and back bead width than the Ti-3Al-2.5V. It can also be seen that at 0.5 mm arc length, weld current of 60 A with different speed (low heat input), the difference in surface and back bead width between the two alloys is not significant. At 1.0 mm arc length, weld current 70 A with different speed (medium heat input), the bead width difference is prominent. At higher heat input (1.5 mm arc length, weld current 80 A) and different speeds, the bead width difference becomes wider. Therefore, the Ti-6Al-4V welds have a wider surface bead width and back bead width than Ti-3Al-2.5V welds in the same welding conditions in

Table 5 Mean multi-response ratio for welding performance of Ti-6Al-4V and Ti-3Al-2.5V

Welding parameters	Mean multi repose ratio (db)									
	Ti-6Al-4V					Ti-3Al-2.5V				
	Level 1	Level 2	Level 3	Δ	Rank	Level 1	Level 2	Level 3	Δ	Rank
Arc length (mm) , A	8.46	8.83	8.32	0.51	3	7.86	2.37	5.71	5.48	3
Welding current (A), B	0.86	7.76	16.99	16.12	1	0.29	6.44	9.20	8.90	2
Welding speed (m/s), C	16.15	6.52	2.95	13.20	2	10.71	5.11	0.12	10.59	1

Fig. 3 Comparison of surface bead width and back bead width with a different heat input of welds of Ti-6Al-4V and Ti-3Al-2.5V (Arc length and current varies from 0.5 mm to 1.5 mm and 60 A to 80 A, respectively)

most of the heat input. When the heat input increases, the difference in bead width becomes significant.

4.4 Microstructure of Titanium Alloys at optimum conditions

The microstructure of base metal microstructure and weld zone of two alloys are shown in Fig. 4(a) and 4(b). Ti-6Al-4V base metal shows alpha (white) grain with areas of beta (black) phase at grain boundaries. Ti-3Al-2.5V base metal consists of a fine equiaxed alpha phase mixed with a transformed beta phase. During the welding process, the base metal is subjected to rapid heating and transforms into a liquid. On the reverse, during solidification, β grain growth takes place. This β is decomposed in the solid-state on further cooling. The decomposition can take place either diffusion aided transformation to α -phase or diffusionless transformation to a martensite phase or mixture of both. A mixture of α -martensite, and retained β phase may also be observed.

In optimal welding conditions (arc length 1.5 mm,

weld current 70 A and welding speed 300 mm/min), the microstructure of WZ (weld zone) of both alloys consists of α' -martensite (Fig. 4(c), (d)) and α'' -martensite (Fig. (e) and (f)). The welded zone of Ti-6Al-4V may entirely experience diffusionless transformation and thereby consisted of a full martensite structure. This microstructure occurred when untransformed β subjected to a temperature below the martensite start temperature during cooling⁹). There could be a presence of some alpha, but it is often difficult to distinguish from a microscopic view. The dark point in the fusion zone of Ti-3Al-2.5V (Fig. 5), which is presumably retained β , is absent in the Ti-6Al-4V weld zone. This might indicate the transformation of Ti-3Al-2.5V weld zone start at a temperature above the martensite temperature and arrest some beta fraction in the welded zone during cooling⁹).

The dissimilar welding (Fig. 6(a)) of these two alloys shows that Ti-3Al-2.5V side contains white areas in the weld zone and HAZ compared to Ti-6Al-4V. A close

Fig. 4 Microstructure of (a) base metal, (c) α' -martensite in a welded, (e) α'' -martensite in a welded zone for Ti-6Al-4V, (b) base metal, (d) α' -martensite in a welded, (e) α'' -martensite in a welded zone Ti-3Al-2.5V

Fig. 5 Retained β as a mixture of α -martensite in Ti-3Al-2.5V welded zone

inspection of the weld zone confirms that the martensite structure is more intense in the Ti-6Al-4V side compared to Ti-3Al-2.5V. Needle density in the weld zone microstructure of these two alloys indicates the occurrence of such phenomena (Fig. 6(b) and 6(c)). This reveals that the martensite percentage is higher in Ti-6Al-4V weld zone and HAZ but low content of alpha compared to Ti-3Al-2.5V. It is reported that there could be an increase in martensite due to an increase in

Fig. 6 (a) Macrostructure of dissimilar welding of Ti-6Al-4V and Ti-3Al-2.5V, (b) Martensite in weld zone of Ti-6Al-4V side, and (c) Martensite structure in weld zone of Ti-3Al-2.5V side

heat input for titanium alloys¹⁰. The high heat capacity of Ti-6Al-4V, which causes a high bead width for Ti-6Al-4V, could play a role in increasing the martensite percentage in the Ti-6Al-4V weld zone compared to the Ti-3Al-2.5V.

4.5 Hardness

Fig. 7 illustrates the microhardness distribution in base metal, HAZ, and weld zone for the Ti-6Al-4V and Ti-3Al-2.5V in optimal welding conditions. Vickers microhardness measurement shows a variation in value across the section which is measured at a pitch distance of 0.5 mm with a load of 500 g. For base metal, HAZ, and weld metal, Ti-6Al-4V shows higher hardness than Ti-3Al-2.5V. It is reported that the presence of stabilized beta decreases the hardness of martensite¹¹. Vanadium is considered as a beta stabilizing element. The weight percentage of vanadium in Ti-6Al-4V is higher than the Ti-3Al-2.5V, which might increase the hardness in all zones of Ti-6Al-4V.

It is reported that the martensite percentage in the weld zone could also increase the hardness in GTA welding of titanium alloys¹⁰. The high percentage of martensite in the weld zone of Ti-6Al-4V could also have an impact on high hardness compared to Ti-3Al-2.5V. The crystal structure of α' -martensite and α'' -martensite in the welded zone of these two titanium alloys is hexagonal and orthorhombic structure. The XRD analysis of the welded zone structure showed the Ti-6Al-4V contains more hexagonal structure (α' -martensite) and intensity is high compared to Ti-3Al-2.5V (Fig. 8). This might suggest Ti-6Al-4V weld zone contains more martensite than the Ti-3Al-2.5V, which causes the high hardness in the welded zone of Ti-6Al-4V.

Fig. 7 Hardness profile of weld zone for (a) Ti-6Al-4V and (b) Ti-3Al-2.5V

Fig. 8 X-ray diffraction (XRD) analysis of the welded zone of Ti-6Al-4V and Ti-3Al-2.5V

4.6 Tensile test

The tensile tests were carried out for the two base metals and welded samples (optimal condition) to find out the strength and fracture location based on ASTM E-8. The fractured specimens are shown in Fig. 9. Ti-6Al-4V possesses higher tensile strength and lower elongation (Fig. 10(a) and (b)) compared to that of

Fig. 9 Fractured specimen in tensile test (welded) (a) Ti-6Al-4V and (b) Ti-3Al-2.5V

Ti-3Al-2.5V. The higher amount of beta phase (base metal beta) is responsible for the higher tensile strength of Ti-6Al-4V^{12,13}. However, Ti-6Al-4V exhibits low elongation compared to Ti-3Al-2.5V (Fig. 10(b)) due to the coarser beta phase. Both the welded Ti-6Al-4V and Ti-3Al-2.5V samples show lower elongation than base metal samples with the same base metal failure. It can be understood with the effects of microstructural changes in the heat-affected zone during the welds.

5. Conclusions

1) The bead geometry of titanium alloys is optimized by the Taguchi method. At optimal welding conditions, the bead width of Ti-6Al-4V is wider than the Ti-3Al-2.5V due to the lower thermal conductivity and higher heat capacity of Ti-6Al-4V.

2) Welding current is the most influencing factor for Ti-6Al-4V, whereas welding speed is the most influencing factor for Ti-3Al-2.5V. This is confirmed as another reason for the wider bead width in Ti-6Al-4V. With increasing heat input, the difference in bead width between the two alloys becomes more prominent.

3) At optimal parameters, the weld zone of both Ti-6Al-4V and Ti-3Al-2.5V consisted mainly of martensite structure. However, Ti-3Al-2.5V contains a small amount of retained β in the weld zone, which is not observed in Ti-6Al-4V weld metal.

4) During the tensile test of the welds, a fracture occurred in the base metal portion. Ti-6Al-4V shows higher tensile strength than Ti-3Al-2.5V as the base met-

Fig. 10 Comparison of (a) tensile strength and (b) elongation for base metal and welded samples

al of Ti-6Al-4V contains a high amount of beta phase compared to Ti-3Al-2.5V.

ORCID: Nazmul Huda: <https://orcid.org/0000-0001-5857-5278>

ORCID: Jae Won Kim: <http://orcid.org/0000-0001-6984-3282>

ORCID: Changwook Ji: <http://orcid.org/0000-0002-5158-5243>

ORCID: Dae-Geun Nam: <http://orcid.org/0000-0003-2360-722X>

ORCID: Yeong-Do Park: <http://orcid.org/0000-0002-0165-4749>

Acknowledgment

This Work was supported by Dong-Eui University Foundation Grant (2020)

References

1. H. K. Lee, H. S. Han and J. Son, The Effects of Welding Parameters on the Weld Shape in Pulsed GTA Welding of a STS304L Stainless Steel Capsule, *J. Weld. Join.* 25(5) (2007) 64-71.
<https://doi.org/10.5781/KWJS.2007.25.5.064>
2. Y. N. Ahn and C. H. Kim, Yb:YAG Laser and Electron Beam Welding of Ti-6Al-4V Alloy, *J. Weld. Join.* 29(6) (2011) 4-8.
<https://doi.org/10.5781/KWJS.2011.29.6.624>

3. C. E. Bull, K. A. Stacey and R. Calcraft, On-line weld monitoring using ultrasonics, *J. Nondestruct. Testing*, 35(2) (1993) 57-64.
[https://doi.org/10.1016/0308-9126\(90\)91601-O](https://doi.org/10.1016/0308-9126(90)91601-O)
4. C. M. D. Starling, P. V. Marques and P. J. Modenesi, Statistical modelling of narrow-gap GTA welding with magnetic arc oscillation, *J. Mater. Process. Tech.* 51(1-4) (1995) 37-49.
[https://doi.org/10.1016/0924-0136\(94\)01356-6](https://doi.org/10.1016/0924-0136(94)01356-6)
5. N. Xiansheng, Z. Zhenggan, W. Xiongwei and L. Luming, The use of Taguchi method to optimize the laser welding of sealing neuro-stimulator, *Opt. Laser Eng.* 49(3) (2011) 297-304.
<https://doi.org/10.1016/j.optlaseng.2010.11.005>
6. A. S. H. Kabir, X. Cao, P. Wanjara, J. Cuddy, A. Birur, and M. Medraj, Use of filler wire for laser welding of Ti6Al-4V, *Canadian Metall. Quart.* 51(3) (2012) 320-327.
<https://doi.org/10.1179/1879139512Y.0000000016>
7. G. Wexsch, R. Boyer and E. W. Collings, Materials Properties Handbook: Titanium Alloys, *ASM International* (1994).
8. Y. S. Tarn and W. H. Yang, Optimization of the weld bead geometry in gas tungsten arc welding by the Taguchi method. *Int. J. Adv. Manuf. Tech.* 14(8) (1998) 549-554.
<https://doi.org/10.1007/BF01301698>
9. J. W. Elmer, T. A. Palmer, S.S. Babu and W. Zhang, Phase transformation dynamics during welding of Ti-6Al-4V, *J. Appl. Phys.*, 95(12) (2004) 8327-8339.
<https://doi.org/10.1063/1.1737476>
10. R. Reda, M. Magdy and M. Rady, Ti-6Al-4V TIG Weld Analysis Using FEM Simulation and Experimental Characterization, *Iran J. Sci. Technol. Trans. Mech. Eng.* 44 (2020) 765-782.
<https://doi.org/10.1007/s40997-019-00287-y>
11. A. B. Short, Gas tungsten arc welding of $\alpha+\beta$ titanium alloy: a review, *Mater. Sci. Tech.* 25(3) (2009) 309-324.
<https://doi.org/10.1179/174328408X389463>
12. T. Grosdidier, Y. Combres, E. Gautier and M. J. Phlippe, Effect of microstructure variations on the formation of deformation-induced martensite and associated tensile properties in a β metastable Ti alloy, *Metall. Mater. Trans. A*, 31(4) (2000) 1095-1106.
<https://doi.org/10.1007/s11661-000-0105-3>
13. C. M. Yu, S.Y. Kim, J. H. Park, G.J. Seo, S. M. Cho, A Study on Deformation According to Welding Speed of Root Pass in GTAW Butt Joint Welding, *J. Weld. Join.* 37(5) (2019) 493-500.
<https://doi.org/10.5781/JWJ.2019.37.5.9>