

DOI: <https://doi.org/10.24425/amm.2023.141486>YONG-JAE LEE¹, WON-KI JEONG¹, SEUNG-JUN LEE², HIDETOSHI FUJII³,
SE EUN SHIN¹, DONG-GEUN LEE^{1*}

EFFECT OF WELDING CONDITIONS ON MICROSTRUCTURAL EVOLUTION OF FRICTION-STIR-WELDED Ti-Cu PLATE

Fusion welding of Ti-Cu is difficult because of big difference of melting points and formation of brittle intermetallic compounds. Friction stir welding is carried out by solid-state joining, thermo-mechanical stirring, and friction heat. Ti-Cu FSW dissimilar welding can supply a very sound joint area with a few intermetallic compounds. Optimized welding process conditions are essential to obtain suitable microstructure and mechanical properties of welded zones. Different welding speeds affect the evolution of microstructure and mechanical properties due to changes of input heat and internal stored deformation energy. The correlation of microstructure and mechanical properties of Ti-Cu welded zone according to welding speeds were investigated and analyzed. As the higher the welding speed, the lower the heat input and the lower the temperature rise. Ti-Cu 75 has the smallest grain size at 13.9 μm , but the optimum mechanical properties and the integrity of welding were shown in Ti-Cu 50.

Keywords: Friction stir welding; Ti-Cu dissimilar welding; intermetallic compounds; welding speed

1. Introduction

It is important to use materials with high thermal conductivity for efficient heat transfer of a heat exchanger, and high corrosion resistance of materials should also be excellent because industrial wastewater with high temperature flows along the tubes inside the heat exchanger. Titanium with excellent mechanical properties in wide temperature ranges and high corrosion resistance has been studied to weld with copper that has excellent heat transfer due to its high thermal conductivity in order to use it as a material for the heat exchanger [1-3]. Titanium and its alloy materials, however, have low thermal conductivity during fusion welding and strong oxygen affinity at high temperatures, resulting in problems such as grain coarsening and high-temperature oxidation, and degrading mechanical properties of the welding zone and heat affected zones [4,5]. Copper is prone to cracks as its parts containing copper oxide melt first during welding, and since the thermal expansion factor is large, it can cause shrinkage and stress concentration caused by cooling, which can lead to cracks.

Conventional welding methods, which operate at high welding temperatures, can worsen the quality of the product through increasing heat affected zones and facilitating the formation of

intermetallic compounds (IMCs) [6,7], which are prone to cracks in the dissimilar welding of titanium-copper [8]. Therefore, it may be advantageous to apply friction stir welding (FSW), which is a type of solid-state welding, to dissimilar welding in order to reduce process costs and to address material degradation in the welding zone. The FSW is a solid-state welding conducted by inserting a dedicated tool into the material and rotating it, and friction and friction heat become the driving force of dynamic crystallization, which can strengthen the strength of the welding zone [9]. Also, it can prevent mechanical degradation because of minimizing the high temperature oxidation and intrusion of activated gases as the temperature of the material does not rise above the transformation point, unlike fusion welding.

In this study, the FSW was successfully applied for the dissimilar welding of copper and titanium, and the structural integrity of the welding zone was evaluated according to the change in welding speeds. Then, the microstructural differences between the advancing side and the retreating side were observed and analyzed in conjunction with mechanical properties. This work can be to provide basic research and database for use as parts that require both corrosion resistance and thermal conductivity such as heat exchangers.

¹ SUNCHON NATIONAL UNIVERSITY, DEPARTMENT OF MATERIALS SCIENCE AND METALLURGICAL ENGINEERING, SUNGHEON, 57922, REPUBLIC OF KOREA

² KOREA POLYTECHNIC UNIVERSITY, DEPARTMENT OF ADVANCED MATERIALS ENGINEERING, SIHEUNG, 15073, REPUBLIC OF KOREA

³ OSAKA UNIVERSITY, JOINING AND WELDING RESEARCH INSTITUTE, OSAKA 567-0047, JAPAN

* Corresponding author: leechodg@snu.ac.kr



2. Experimental

2.1. Friction stir welding

ASTM Gr. 2 pure titanium and pure Copper (99.95 wt.%) sheets with each thickness of 2 mm were fabricated respectively for the FSW of dissimilar materials of pure Ti and Cu. The rotational speed of the tool was equal to 500 rpm with the joining of Ti and Cu materials, and the welding speed was varied by 25 mm/min (Ti-Cu 25), 50 mm/min (Ti-Cu 50), and 75 mm/min (Ti-Cu 75) to conduct the FSW. Here, the tool for the FSW was made of tungsten carbide (WC) with a shoulder size of 12 mm and a diameter of 4 mm, and the advancing angle was set at 3°. The tool is divided into the advancing side (AS) with the same direction of rotation and progress, and the retreating side (RS) with the reversed direction, and metal flows and thermal history vary depending on the zones. In this experiment, the AS and RS areas were placed in Ti and Cu respectively, and the tool was offset by 0.2 mm to the direction of Cu.

2.2. Investigation of microstructure and evaluation of mechanical properties

An optical microscope (OM, BX53M, Olympus) and a scanning electron microscope (SEM, JSM-7001F, JEOL) were used to investigate changes in the microstructure of Ti and Cu in the FSW process. Also, an electron backscatter diffraction (EBSD) device was also used. The welding zone was divided into the base metal (BM), heat affected zone (HAZ), thermal-mechanical affected zone (TMAZ), and stir zone (SZ). An X-ray diffraction (XRD) was used to determine the presence of intermetallic compounds and to verify its types in the stir zone.

In order to analyze tensile properties according to the process conditions in the dissimilar FSW process of Ti and Cu, plate-type tensile test samples with a length and width of 48×10 mm and a point distance of 20 mm were precisely fabricated and experimented with a hydraulic universal material testing machine (DSCK, Ssaui Bestech). The hardness test was performed using a Vickers hardness test (HM-200, Mitutoyo) system by maintaining the base material, heat affected zone, thermal-mechanical affected zone, and stir zone for 15 seconds with a load of 0.3 kgf for each zone.

3. Results and discussion

3.1. Microstructure

In the results of observing the welding zones of the Ti-Cu 25~Ti-Cu 75 macroscopically using a dissecting microscope (Fig. 1(a)-(c)), defects and burrs occurred in the middle of the welding zones at the welding speeds of 25 mm/min and 75 mm/min, and the structural integrity was relatively excellent at 50 mm/min. In the results of the observation of the microstructures, as shown in Fig. 1(d)-(f), one of the typical defects, voids were observed in all conditions [10], and all defects occurred in the Cu area. In the Cu area, it is possible to observe onion ring patterns, which show plastic flow of the materials produced by heat [11]. During FSW, the metal flow is interrupted by large fragments, which are produced from a strong material and enter a relatively soft material [8]. Thus, the produced fragments cause defects such as voids in the soft material. As the welding speed is slower (increasing the heat input), the greater is the inflow of fragments from Ti to Cu.

Because the coefficient of diffusion of Ti in Cu ($D_{Ti/cu} = 0.693 \cdot 10^{-4} \exp[-(196 \text{ kJmol}^{-1}/RT)] \text{ m}^2\text{s}^{-1}$) is about twice as large

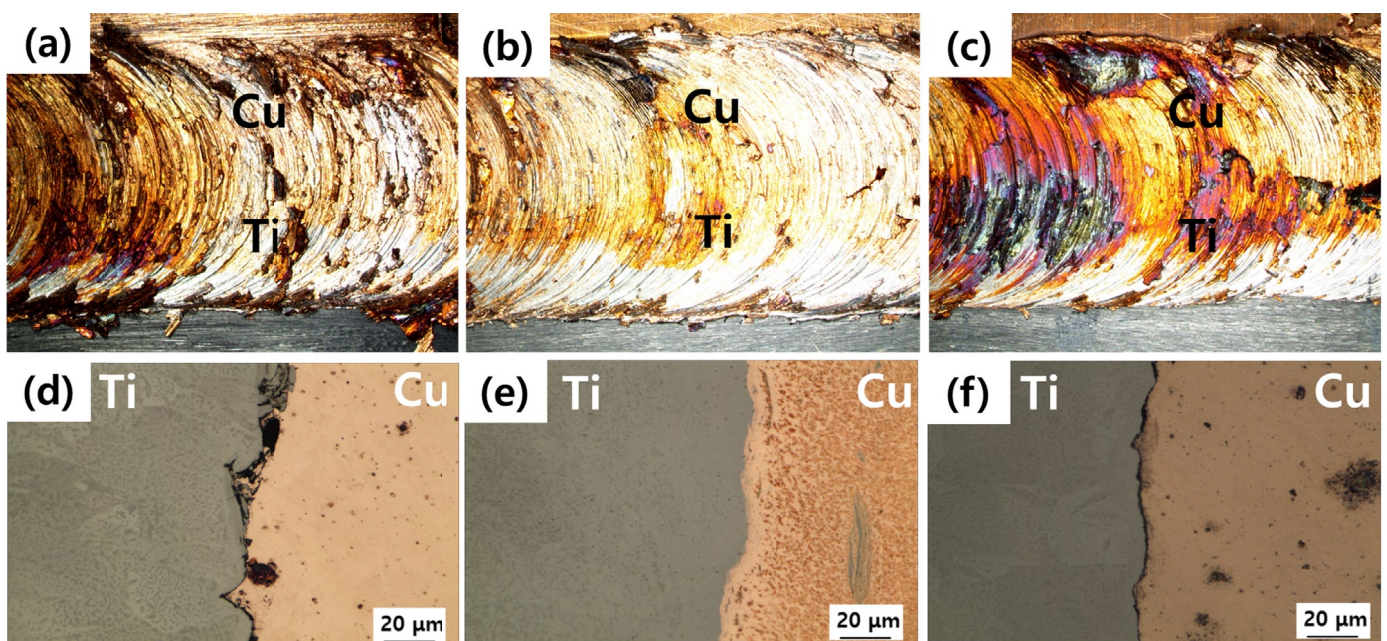


Fig. 1. Stereoscopic images of FSWed surface at each welding conditions; (a) Ti-Cu 25, (b) Ti-Cu 50, and (c) Ti-Cu 75. Cross-sectioned macrographs of FSWed zone; (d) Ti-Cu 25, (e) Ti-Cu 50, and (f) Ti-Cu 75

as that of Cu in Ti ($D_{\text{Cu/Ti}} = 3.8 \cdot 10^{-5} \exp[-(195 \text{ kJmol}^{-1}/RT)] \text{ m}^2\text{s}^{-1}$), it is easier for Ti to diffuse in Cu than Cu in Ti. This diffusion produces intermetallic compounds between dissimilar materials. In the results of the XRD analysis, as shown in Fig. 2(a)-(b), it showed that the intermetallic compounds such as TiCu, Ti_3Cu_4 , and Ti_2Cu were produced and Ti_3Cu_4 and Ti_2Cu were produced sequentially from TiCu, which has low free energy [12]. As a result of comparing and analyzing the XRD graph of Ti-Cu 25 and Ti-Cu 50, the intensity value of intermetallic compounds was lower in the Ti-Cu 50 sample with lower heat input than Ti-Cu 25. It can be seen that the peak values (Ti_2Cu , Ti_3Cu_4) appeared in Ti-Cu 25, but did not appear in Ti-Cu 50. One of the defects caused by the difference in diffusion rates between dissimilar metals is the Kirkendall void. In the stir zone of Ti-Cu metals, it is easier for Ti atoms to diffuse in Cu matrix due to the difference in diffusion coefficient, which there is a double difference as mentioned above. As a result, a Kirkendall voids, which are seen as black dots in Fig. 3, were observed. It can be seen that relatively large amounts of voids were observed at 25 mm/min, where the heat input was the greatest.

3.2. Hardness

After cutting the samples into a vertical plane in the direction of welding progress, the hardness values were measured at a certain interval from BM of Ti to BM of Cu. Fig. 2(c) represents the changes in hardness values. Overall, it shows that the hardness of the stir zone is higher than that of the base metal. During the friction stirring process, extreme plastic deformations create twins in the stir zone and unstable conditions caused by

the deformation energy in the stir zone act as a driving force for dynamic recrystallization. Therefore, the grains of the stir zone are finer than the base metal, and that lead to increase the hardness value according to the Hall-Petch equation.

As the slower welding speed increases the pressure of the tool acting on the sample per unit time and the local number of rotations, it increases heat input and decreases cooling speed. Thus, an annealing effect is applied to the welding zone, and that causes grain coarsening after the dynamic recrystallization. In the results of the EBSD observation, the average grain sizes of the Ti-Cu 25 to Ti-Cu 75 were 16.8 μm , 15.2 μm , and 13.98 μm (Fig. 3), respectively, in which the faster the welding speed, the smaller the size is. The average hardness values in the AS (Ti) zone were presented by Ti-Cu 25 > Ti-Cu 75 > Ti-Cu 50. The Ti-Cu 75 showed a higher hardness value because of its smaller grain size due to the lower heat input than the Ti-Cu 50. Ti-Cu 25 had the largest grain size, but showed the highest hardness value. Generally, high hardness and brittle martensite, not alpha phase, can be produced when rapidly cooled in the beta phase region. Accordingly, due to the very slow welding speed of Ti-Cu 25, the amount of heat input is very large, and the martensitic transformation phase by rapid cooling exists in the region where the temperature is increased to some beta phase regions, thereby Ti-Cu 25 exhibiting high hardness despite partial grain growth.

At points above 150 Hv in the RS (Cu) area, it shows higher values than the average (110 Hv) because of producing intermetallic compounds. The Ti-Cu 75, which has the fastest welding speed and the small heat input compared to other conditions, can be found to have a narrow range of producing intermetallic compounds (hardness points above 150 Hv) from the interface of Ti/Cu.

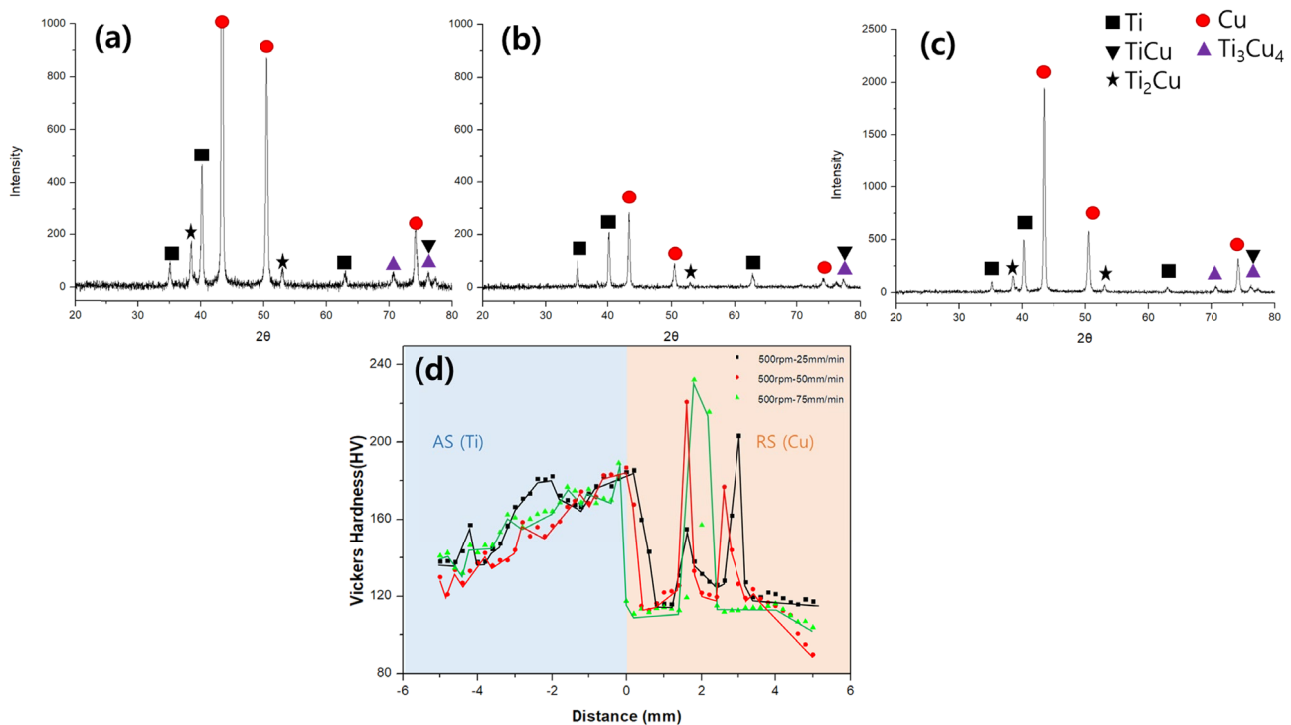


Fig. 2. (a) X-ray diffraction analysis of the stir zone; (a) Ti-Cu 25 (b) Ti-Cu 50, (c) Ti-Cu 75 and (d) Vickers hardness distribution of the cross-sectioned FSWed zone according to welding conditions

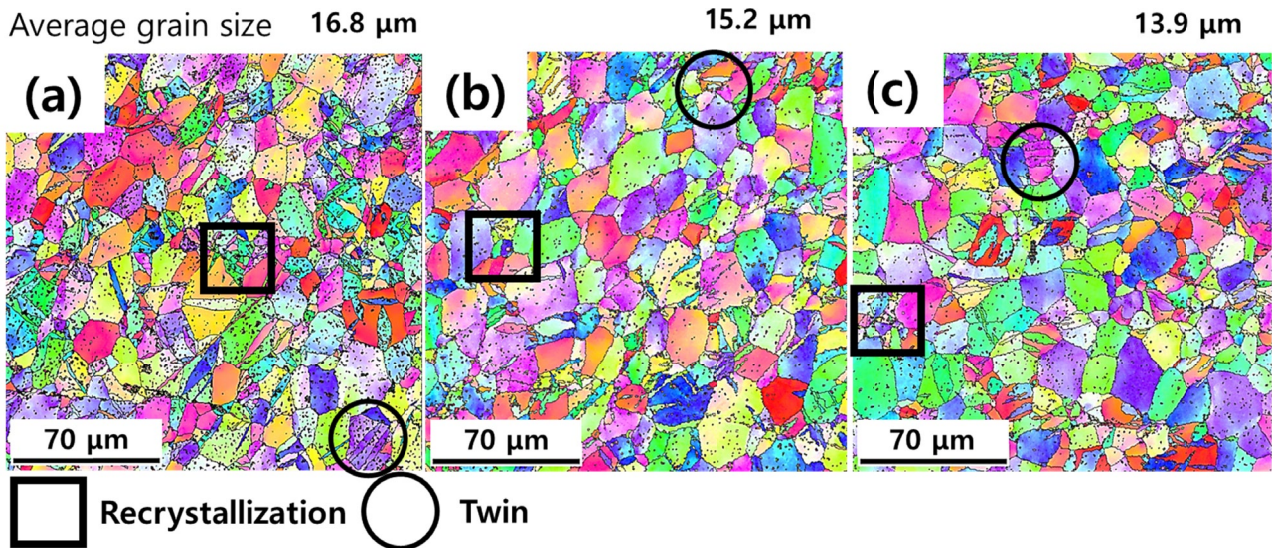


Fig. 3. EBSD analysis of Ti stir zone for each sample; (a) Ti-Cu 25, (b) Ti-Cu 50, and (c) Ti-Cu 75

3.3. Tensile properties

As a result of evaluating the welding region of Ti/Cu and room temperature tensile properties according to the welding conditions (TABLE 1), all samples were fractured at the junction. Due to the heat of FSW, intermetallic compounds were generated in the SZ region, so no yielding phenomenon occurred and fracture occurred in the elastic region. Ti/Cu intermetallics are the main cause of fracture as they have brittle properties among intermetallic compounds. Therefore, it had a value lower than the strength of the base metal (Ti, Cu).

TABLE 1

Tensile properties of the Ti-Cu FSWed samples

Samples	Tensile Properties	
	UTS (MPa)	YS (MPa)
Pure Cu	210 \pm 3	35 \pm 4
Pure Ti	345 \pm 2	275 \pm 7
Ti-Cu 25	121 \pm 5.2	120 \pm 4.6
Ti-Cu 50	147 \pm 7.1	140 \pm 5.6
Ti-Cu 75	56 \pm 2.5	52 \pm 3.5

The tensile and yield strength values of the Ti-Cu 50 were higher than the Ti-Cu 25. As shown in the results of the hardness measurement, this is because the Ti-Cu 50 has a larger potential density due to its plastic deformation and a smaller grain size due to a relatively small amount of heat input. However, the tensile strength and yield strength values of the Ti-Cu 75 are lower than that of other samples. It requires solid-state welding with sufficient heat input and softening of the material during the welding process, but fast welding speeds lead to poor plastic flow and cause poor welding and multiple defects around the welding zone [13]. Under the welding conditions of the Ti-Cu 75, a number of defects were found in the interface of the junction to weaken the welding compared to other conditions (Fig. 1).

4. Conclusions

1. The sound welding zone could be obtained by Ti-Cu FSW process, which is a solid-state welding process of dissimilar materials. It was confirmed that intermetallic compounds such as Ti_2Cu and Ti_3Cu_4 , were formed in the SZ region of Cu side due to the high diffusion rate of Ti atoms in Cu matrix.

2. Under the same rotational tool speed, as the welding speed of the tool becomes slow, the amount of heat input increases and the cooling rate becomes slower. As a result, an annealing effect occurs and it causes relatively lower hardness and strength values due to grain growth.

3. The faster the welding speed, the less softening by lower heat input is achieved in the welded zone. And the metal flow does not work smoothly, and plastic deformation occurs rough and unstable. This causes internal defects in the welded zone to degrade the integrity of the welding. Finally, the optimum sound welds and good mechanical properties could be obtained from the sample under the conditions of 500 rpm-50 mm/min.

Acknowledgments

This work was supported by a Research Promotion Program of SCNU.

REFERENCES

- [1] F.C. Liu, J. Liao, Y. Gao, K. Nakata, Influence of texture on strain localization in stir zone of friction stir welded titanium, *J. Alloys Compd.* **626**, 304-308 (2015).
- [2] C.S. Youn, Y.K. Park, H.W. Lee, D.-G. Lee, Study for Heat Treatment Optimization of Titanium Hollow Casted Billet, *J. of the Korean Society for Heat Treatment* **32**, 68-73 (2019).
- [3] C.S. Youn, Y.K. Park, J.H. Kim, S.C. Lee, D.-G. Lee, Aging Treatment Optimization of Ti-3Al-8V-6Cr-4Mo-4Zr Alloy for

- Spring Application, J. of the Korean Society for Heat Treatment **30**, 279-284 (2017).
- [4] Y.J. Lee, A. Choi, S.J. Lee, H. Fujii, S.E. Shin, D.-G. Lee, Microstructure and Mechanical Properties of Pure Titanium Processed using Friction Stir Welding, J. of the Korean Society for Heat Treatment **32**, 124-130 (2019).
- [5] Z. Yang, B. Qi, B. Cong, F. Liu, M. Yang, Microstructure tensile properties of Ti-6Al-4V by ultrahigh pulse frequency GTAW with low duty cycle, J. Mater. Process. Technol. **216**, 35-47 (2015).
- [6] C. Guo, J. Zhou, Y. Yu, L. Wang, H. Zhou, J. Chen, Microstructure and tribological properties of Ti-Cu intermetallic compound coating, Mater. Des. **36**, 482-489 (2012).
- [7] M.R. Akbarpour, S. Moniri Javadhesari, Wear performance of novel nanostructured Ti-Cu intermetallic alloy as a potential material for biomedical applications, J. Alloy. Comp. **699**, 882-886 (2017).
- [8] V.N. Eremenko, Y.I. Buyanov, S.B. Prima, Phase diagram of the system titanium-copper, Powder Metall. Met. Ceram. **5**, 494-502 (1966).
- [9] W.B. Lee, C.Y. Lee, W.S. Chang, Y.M. Yeon, S.B. Jung, Microstructural investigation of friction stir welded pure titanium, Mater. Lett. **59**, 3315-3318 (2005).
- [10] T.J. Yoon, M.C. Kang, C.Y. Kang, Effects of Welding Conditions and Material Arrangement on Tensile Properties of Friction Stir Lap Welded of Dissimilar Al Alloy, A5J32/A5052, J. Kor. Powd. Met. Inst. **20**, 302-307 (2013).
- [11] T. Sakthivel, J. Mukhopadhyay, Microstructure and mechanical properties of friction stir welded copper, J. Mater. Sci. **42**, 8126-8129 (2007).
- [12] Y.D. Zhu, M.F. Yan, Y.X. Zhang, C.S. Zhang, First-principles investigation of structural mechanical and electronic properties for Cu-Ti intermetallics, Comput. Mater. Sci. **123**, 70-78 (2016).
- [13] H. Fujii, Y. Sun, H. Kato, K. Nakata, Investigation of welding parameter dependent microstructure and mechanical properties in friction stir welded pure Ti joints, Mater. sci. Eng. A **527**, 3386-3391 (2010).