The effect of Zn interlayer on microstructure and mechanical performance during TIG overlap welding-brazing of Al to Ti

Xiaofeng Li, Caixia Li, Zhiliang Cao and Ping Yang
Institute of Intelligent manufacturing and automotive, Chongqing Technology and Business Institute, Chongqing 401520, People’s Republic of China

Abstract
Tungsten inert gas welding-brazing technology was investigated to achieve the sound joining of Al-Ti alloys with the addition of Zn interlayer. Experiment results show that the Zn interlayer was beneficial to enhance the wettability of weld metal on Ti alloy substrate and improve the weld appearance. With low heat input, a Zn rich layer was observed near the brazing zone. As the heat input increased, TiAl3 phase was generated in fusion area and the morphology of interfacial brazing layer changed from lamellar to serrate. With the welding current increased to 85A, the micro hardness of fusion area fluctuation owing to the excessive formation of TiAl3 phase. Under the optimal welding current of 75A, the sound Al-Ti weldment with the maximum tensile strength of 175MPa was obtained. Eventually, the improvement mechanism of wettability was investigated.

1. Introduction

The expansion of multiple materials application in vehicle industry is an efficient way to improve fuel economy and reduce greenhouse gas emissions [1–3]. In recent years, Al alloys are extensively used as light metallic materials with the excellent comprehensive performances, such as low density, high strength ratio, superior corrosion resistance and strong deformation ability [4–6]. Besides, Ti alloys with its excellent properties have attracted more attention in the pursuit of lightweight vehicle [7–9]. It is apparent that, the dissimilar metals joining of Al-Ti can achieve the purpose of lightweight equipment [10–12].

A series of welding methods have been studied for the joining of Al-Ti dissimilar metals, such as laser welding (LW) [13, 14], diffusion welding (DW) [15, 16], friction stir welding (FSW) [17, 18], brazing [19, 20] and resistance spot welding (RSW) [21, 22], etc. Note that welding-brazing technology, as a low-cost and high-efficiency joining method, was widely studied for the heterogeneous metals welding [23, 24]. The most typical characteristic of welding-brazing technology is that the joint shows dual welding features of fusion welding and brazing, which was experimentally proved to be beneficial to improve joint quality. For example, zhao et al [25] investigated the evolution of joint appearances, interfacial microstructure and mechanical performance of Mg-steel joint welded by welding-brazing technology. Experimental results show that AlNi + (α-Mg + Mg2Ni) eutectic formed at the seam area and bulky Mg2Ni intermetallic compound occurred in the matrix of Mg-Ni eutectic. With optimized welding parameters, the sound Mg-steel weldment with the maximum tensile-shear load of 230 N mm–1 was obtained, reaching an 88.5% joint efficiency relative to Mg alloy parent material. Zhang et al [26] studied the effect of heat input on microstructure and joining strength of Ti-Al butt joints obtained by double-sided arc welding-brazing process. According to Zhang, acceptable TiAl6V4/5A06 weldment with fine front and back surface appearances were obtained by welding-brazing technology. And the morphology, composition and thickness of intermetallic compounds evolved with the increase of welding heat input. Under
welding current of 80–90 A, welding speed of 15 mm s\(^{-1}\) and TIG position of 0 mm, the Ti-Al joint had optimal joining strength of 240.3 MPa.

The literatures reveal that welding-brazing technology is beneficial to achieve reliable joining between heterogeneous metals with considerable physical and chemical properties. However, Wang et al.\(^{[27]}\) reported that during the welding-brazing of Al-Ti, liquid Al alloy molten metal was easy to oxidize and showed inferior wetting and spreading properties on the surface of Ti alloy base metal, which resulted in poor weld appearance and low welding strength. Eventually, in the present study, a Zn interlayer was used to assure fine spreading ability and weld performance. According to Dharmendra et al.\(^{[28]}\), Zn interlayer was successfully applied to enhance the wetting and spreading ability of molten pool during the welding-brazing of Al-steel. It is evident that the addition of alloying elements is a momentous topic for further research.

In the present paper, dissimilar metals of Al-Ti were joined in an overlap configuration by TIG welding-brazing process. And the Zn foil was used as interlayer metal. The mechanical performances and microstructural evolution of Al-Ti joints were investigated by means of mechanical testing and microscopy techniques.

### 2. Materials and methods

In the present study, 5052 Al alloy and Ti6Al4V alloy were used as base materials during the TIG welding-brazing experiments. The tensile strength of 5052 Al alloy and Ti6Al4V alloy are respectively 225 MPa and 850 MPa. The dimensions of above two parent plates were machined to 70mmx60mmx1 mm and the oxide layer was polished (800# sandpaper) prior joining experiment. The \(\varphi 0.8\) Al-5Si alloy wire was applied as filler metal. Table 1 presents the chemical compositions of all base materials. Figure 1 depicts that the Al alloy base metal was fixed on the top of Ti alloy in the lap joint configuration. An YC-300 TIG machine was applied to complete the welding-brazing experiment. The 30-\(\mu\)m-thick Zn foil was selected as interlayer and placed between Al-Ti plates. During the welding experiment, tungsten electrode center of welding gun irradiate the edge of aluminum alloy plate. Under the irradiation of electric arc, the Al base metal, filler wire and Zn foil were melted and wetted on the top surface of Ti alloy plate to form the welding joint. Argon was used to prevent oxidation of molten metal. The welding parameters used in the present welding-brazing experiment are presented in table 2.

After welding experiments, the Al-Ti joints were cut perpendicular to the welding progress for microstructure observation and joining strength testing. The weld cross section of joint was ground and polished with different grades of sandpapers, and subsequently observed by an optical microscope (OM) and scanning electron microscope (SEM) to reveal weld forming characteristics. A dwell time of 10 s and a load of 250 g were adopted during Vickers hardness testing. All indentations were sufficiently spaced to avert the formation of strain field induced by adjacent indentations. The tensile samples were polished with sandpapers and subsequently tested with tensile testing machine at room temperature with a constant speed of 1.5 mm min\(^{-1}\). For each welding parameters, 5 repeated experiments were carried out to obtain the final

| Elements          | Al  | Zn  | Mn  | Si  | V   | Ti | Mg |
|-------------------|-----|-----|-----|-----|-----|----|----|
| 5052 Bal.         | 5.8 | 0.1 | 0.25| 4.2 | 2.2 | 2.8|
| Ti6Al4V           |     |     |     |     |     |    |    |
| Filler Bal.       |     |     | 0.1 | 5.0 | 0.15| 0.15|
| Interlayer        |     |     |     |     |     |    |    |

![Figure 1. The schematic of TIG welding-brazing of Al-Ti alloys.](image)
mechanical properties data. Figure 2 shows the schematic drawing of tensile specimen. SEM equipped with energy dispersive x-ray spectrometer (EDS) was used to investigate the microscopic features.

3. Results

3.1. Weld appearance

Figure 3 presents the typical macro morphologies of cross sections of TIG welded-brazed Al-Ti joints obtained with and without Zn interlayer. As shown in figure 3(a), the Al-Ti joint without the aid of Zn interlayer showed poor welding features. It is apparent that the molten Al alloy base metal and welding wire did not satisfactorily wet the solid Ti alloy, which resulted in excessive accumulation of molten metal. Nevertheless, in the case of Al-Ti joint with addition of Zn interlayer, the weld seam has uniform morphology and good wettability, as indicated in figure 3(b).

Previous literatures indicate that alloying elements have a great influence on the wettability and spreadability of liquid metals. For example, Li et al [29] reported that the presence of Zn coating enhanced the wetting of liquid welding wire on the steel substrate. In this paper, a 30-μm-thick Zn foil was used as interlayer to hopefully improve weld forming and joining quality. In order to determine the effect of interlayer addition on weld forming, weld wetting angles and weld widths of Al-Ti joints were measured. Figure 4 shows the schematic diagram of measurement method and the results were illustrated in figure 5. Figure 5 indicates that the wetting angle (θ) of Al-Ti joint with addition of Zn interlayer was less than that of joint without Zn foil, which resulted in the increase of weld width. Besides, it can be found that the weld width of Al-Ti joint increased along with the

Table 2. Welding parameters of TIG welding-brazing technique.

| Welding current | Welding voltage | Welding speed | Wire feed rate | Shielding gas |
|-----------------|-----------------|---------------|---------------|---------------|
| 55–85A          | 12V             | 0.2 m min⁻¹   | 0.6 m min⁻¹   | 10 l min⁻¹    |

Figure 2. The schematic drawing of tensile specimen.

Figure 3. The typical macro morphologies of cross sections of Al-Ti joints: (a) without interlayer, (b) with addition of Zn interlayer.

Figure 4. The schematic diagram of measurement method.
welding current enhancement. During the welding process, the current determined the effective heat input to base metal. With low heat input, the molten base metal and wire could not adequately wet the Ti alloy and the measured wetting angle was more than 90 degree. With the increase of heat input, both the fluidity of molten metals and the surface activity of Ti alloy increased, which resulted in the decrease of joint wetting angle.

3.2. Microstructure features of Al-Ti joints

Figure 6 shows the typical macroscopic morphology of the weld cross section. Note that the TIG welding-brazing Al-Ti joint was characterized with dual features of brazing and fusion welding. The Al alloy base plate melted and mixed with molten welding wire, and eventually cooled to room temperature to form a fusion zone, indicated by region A. On the other hand, solid Ti alloy metal reacted with the molten Al alloy base metal and welding wire to form the interfacial reaction zone, i.e., brazing zone (indicated by B).

3.2.1. Microstructure of fusion zone

Figure 7 shows the typical backscattered scanning electron microscope (BSE) images of fusion zone produced under Zn interlayer and various welding current. It can be found that the welding current has obvious influence on the microstructure evolution of weld seam. With low heat input (55A), the filler wire and low-melting-point Al alloy base metal received most of the arc heat. And there was not enough heat to complete the melting and sufficient diffusion of Zn, which resulted in the Zn concentration in the grain boundaries near Al-Ti interface, as shown in figure 7(a). With the increasing of heat input (65A), the diffusion of Zn element was strengthened under the stirring action of electric arc. But the Zn diffusion process was still not fully carried out, as presented in figure 7(b). As the current increased to 75A, the microstructure of fusion zone was characterized by sufficient
diffusion of Zn, as indicated in figure 7(c). However, a mass of clubbed intermetallic compounds were formed in the weld seam. EDS results (table 3) revealed that the intermetallic compounds were TiAl3 phase, which was consistent with previous literatures. The formation mechanism of TiAl3 phase was mainly owing to slightly dissolution of Ti from the top surface of Ti alloy base metal to molten metal under the action of enhanced heat input. Under the current of 85A, the number of clubbed intermetallic remarkably increased, attributed to the increased dissolution of Ti, as shown in figure 7(d).

Figure 8 presents the typical EDS area testing results of weld seam obtained with Zn interlayer and various welding parameters. It can be found that Zn atoms aggregated in grain boundary regions as the heat input was insufficient. Conversely, the diffusion of Zn atoms was accelerated by adequate heat input, and finally the Zn atoms were evenly distributed in the weld seam, as presented in figure 8(b). The EDS testing results are consistent with that of microstructural observations.

| Elements (at%) | Al  | Ti  |
|---------------|-----|-----|
| P1            | 72.3| 27.7|
| P2            | 76.5| 23.5|

Table 3. EDS testing results of intermetallic compounds.

diffusion of Zn, as indicated in figure 7(c). However, a mass of clubbed intermetallic compounds were formed in the weld seam. EDS results (table 3) revealed that the intermetallic compounds were TiAl3 phase, which was consistent with previous literatures. The formation mechanism of TiAl3 phase was mainly owing to slightly dissolution of Ti from the top surface of Ti alloy base metal to molten metal under the action of enhanced heat input. Under the current of 85A, the number of clubbed intermetallic remarkably increased, attributed to the increased dissolution of Ti, as shown in figure 7(d).

Figure 8 presents the typical EDS area testing results of weld seam obtained with Zn interlayer and various welding parameters. It can be found that Zn atoms aggregated in grain boundary regions as the heat input was insufficient. Conversely, the diffusion of Zn atoms was accelerated by adequate heat input, and finally the Zn atoms were evenly distributed in the weld seam, as presented in figure 8(b). The EDS testing results are consistent with that of microstructural observations.

3.2.2. Microstructure of brazing zone
Figure 9 shows the BSE images of interfacial reaction zone of Al-Ti joints produced with Zn interlayer and different current. It is apparent that the welding current plays a momentous role in the microstructure features of interfacial reaction layer. Figure 9(a) illustrates that a continuous and thin reaction layer with thickness of
2.2 μm was formed in the brazing zone. The reaction layer has a sheet structure and without any bulge. Figures 9(b) and (c) indicate that the thickness of reaction layer increases with the increase of heat input and the morphology of reaction layer changed from lamellar to serrate. However, under current of 85A, excessive heat input leads to a significant increase in the thickness of the reaction layer, as presented in figure 9(d). Besides, it can be found that some ruptured clubbed intermetallic compounds perpendicular to the Al/Ti interface were
observed, attributed to the electromagnetic stirring effect of electric arc on molten pool. It can be inferred that the excess intermetallic compounds could degrade joint performance.

EDS testing was used to detect the compositions of interfacial reaction layer and the results were listed in Table 4. Based on EDS results, only Ti element and Al element were detected in the reaction layer. The ration of aluminum to titanium is about 3 to 1, indicating the formation of TiAl$_3$ intermetallic compound. The EDS results are consistent with the reaction between liquid Al alloy and solid Ti alloy reported by Chen et al [12].

### 3.3. Micro hardness

The typical micro hardness distribution of Al-Ti joints with different current were measured and illustrated in Figure 10. As presented in figure 10(a), it can be found that the micro hardness of Ti alloy base metal was about 120 HV. But the micro hardness of interfacial reaction layer increased to 153 HV, owing to the formation of TiAl$_3$ intermetallic compound. And the hardness value of fusion zone approximately remained at 95 HV. Figure 10(b) presents the micro hardness distribution of Al-Ti joint under current of 85A. Obviously, the micro hardness values of brazing zone and Ti alloy base metal were similar to that of figure 10(a). However, the marked difference is that the micro hardness of the fusion welding area presented a great fluctuation. Microstructure observations indicated that a large amount of intermetallic compounds were generated in the fusion welding area of joint under current of 85A, resulted in the evolution of micro hardness values.

### 3.4. Mechanical performance

Figure 11 shows the tensile strength of Al-Ti joints welded under different current. It is clear that the heat input markedly affected the mechanical performance of Al-Ti weldments. Under the current of 55A, the Al-Ti joint showed poor tensile strength (96 MPa) owing to deficient metallurgical bonding. However, the tensile strength presented an enhanced tendency as the welding current improved from 55A to 75A, attributed to the strengthening metallurgical bonding. Under optimized welding current of 75A, the maximum tensile strength of 175 MPa was obtained, representing 78% joint efficiency relative to Al alloy parent material. Under the further increase of welding current (85A), the tensile strength reduced to 132 MPa. The above microstructure analysis indicated that the decrease of mechanical performance was mainly attributed to the excessive formation of brittle TiAl$_3$ intermetallic compound.

| Elements (at%) | Al | Ti |
|---------------|----|----|
| P1            | 71.5 | 28.5 |
| P2            | 73.0 | 27.0 |
| P3            | 77.2 | 22.8 |
| P4            | 73.6 | 26.4 |
| P5            | 76.1 | 23.9 |

Table 4. EDS testing results of interfacial reaction layer marked in figure 9.
4. Discussion

With the addition of Zn foil and optimized welding parameters, the Al-Ti joints with sound surface morphology and excellent mechanical performance were obtained. It is obvious that the addition of Zn interlayer effectively improved the wetting and spreading of weld liquid metal on solid Ti alloy plate. Previous literatures reveal that the wetting between solid and liquid metals follows the Young equation:

\[
\cos \theta = \frac{\sigma_{sg} - \sigma_{sl}}{\sigma_{lg}}
\]

where \( \theta \) is the wetting angle, \( \sigma_{sg} \) is the interfacial tension of solid-gas, \( \sigma_{sl} \) is the interfacial tension of solid-liquid, and \( \sigma_{lg} \) is the interfacial tension of liquid-gas (as shown in figure 4). With the assistance of Zn interlayer, the low-melting-point Zn foil melt and even partially evaporated under the heat input of argon arc. Gaseous Zn dissolved into the molten metal and resulted in the formation of relative vacuum at the solid-liquid interface area of the weld. Eventually, \( \sigma_{lg} \) decreased with the increase of external pressure, considering the inertia of system pressure balance. The above formula 1 shows that wetting angle \( \theta \) decreased owing to the decrease of \( \sigma_{lg} \), indicating the improvement of wetting performance. On the other hand, Al-Zn binary phase diagram reveals that the dissolution of Zn interlayer in liquid Al alloy decreased the solidus temperature of molten metal from 923K to about 613K. The solidus temperature of Al alloy (923K) induced considerable temperature difference between the solidification and working temperature of Al-Zn alloy. As reported by Wang et al[27], the above temperature variation is equivalent to improve the wetting temperature and strengthen the spread ability of molten metal.

5. Conclusions

Through investigating the effect of Zn interlayer on TIG welding of Al alloy and Ti alloy by characterization of wetting angle, microstructure features, microhardness distribution and mechanical performance, the following conclusions can be obtained:

i. TIG welding-brazing technology was investigated to achieve the reliable joining of Al-Ti dissimilar alloys. And the addition of Zn interlayer was proved beneficial to improve the wettability of weld metal on Ti alloy substrate.

ii. With low heat input, a Zn rich layer was observed near the brazing zone. As the heat input increased, the morphology of interfacial reaction layer changed from lamellar to serrate.

iii. As the welding current increased from 75A to 85A, the micro hardness of fusion area increased and presented a great fluctuation owing to the formation of TiAl3 phase. Under the current of 75A, the sound Al-Ti weldment with the maximum tensile strength of 175 MPa was obtained.

Figure 11. The mechanical performance of Al-Ti joints welded under different current.
Acknowledgments

This research was financially supported by the Science and technology research support program of Chongqing Education Commission (No. GZTG201614).

ORCID iDs

Xiaofeng Li  @ https://orcid.org/0000-0003-2155-7900
Caixia Li  @ https://orcid.org/0000-0002-7008-0427

References

[1] Xu C, Cheng G M, Sun Y Q, Yuan X J and Jiao Y J 2018 Microstructure and mechanical properties of high energy shot-peened Mg/Ti weldments Sci. Technol. Weld. Join. 23 28–34
[2] Xu C, Cheng G M, Wang H D, Jiao Y J and Yuan X J 2017 Effect of high energy shot peening on the microstructure and mechanical properties of Mg/Ti joints J. Alloys Compd. 695 1383–91
[3] Xu Z W, Li Z W, Xu L and Yan J C 2019 Reduction of intermetallic compounds in ultrasonic assisted semi-solid brazing of Al/Mg alloys Sci. Technol. Weld. Join. 24 163–70
[4] Lin Y J, Yamshu S and Koseki T 2017 Evolution of bonding interface during ultrasonic welding between steel and aluminium alloy Sci. Technol. Weld. Join. 24 83–91
[5] Chu Q, Yang X W, Li W Y, Lu T, Zhang Y, Vairis A and Wang W B 2019 Impact of surface state in probeless friction stir spot welding of an Al–Li alloy Sci. Technol. Weld. Join. 24 200–8
[6] Liu C Y, Zhang B, Ma Z Y, Jiang H J and Zhou W B 2019 Effect of Sc addition, friction stir processing, and T6 treatment on the damping and mechanical properties of 7055 Al alloy J. Alloys Compd. 772 773–81
[7] Ali T, Wang L, Cheng X W, Liu A J and Xu X F 2019 Omega phase formation and deformation mechanism in heat treated Ti–5553 alloy under high strain rate compression Mater. Lett. 236 163–6
[8] Li Y H Z, Ou X Q, Ni S and Song M 2019 Deformation behaviors of a hot rolled near-Ti–5Al–5Mo–5V–1Cr–1Fe alloy Mater. Sci. Eng. A 742 390–9
[9] Chen W, Li C, Zhang X Y, Chen C, Lin Y C and Zhou K C 2019 Deformation-induced variations in microstructure evolution and mechanical properties of bi-modal Ti-55511 titanium alloy J. Alloys Compd. 783 709–17
[10] Yu M R, Zhao H Y, Jiang Z H, Zhang Z L, Xu F, Zhou L and Song X G 2019 Influence of welding parameters on interface evolution and mechanical properties of FSW Al/Ti lap joints J. Mater. Sci. Technol. 35 1543–54
[11] Tian Y B, Shen J Q, Hu S S, Gou J and Kannatey-Asibu E 2019 Wire and arc additive manufactured Ti–6Al–4V/Al–6.25Cu dissimilar alloys by CMT-welding: effect of deposition order on reaction layer Sci. Technol. Weld. Join. 25 73–80
[12] Chen S H, Hua X C, Guo C X, Wei X, Huang J H, Yang J and Lin S B 2019 Interfacial characteristics of Ti/Al joint by vaporizing foil actuator welding J. Mater. Process. Technol. 263 73–81
[13] Lei Z L, Li P, Zhang X R, Wu S B, Zhou H and Lu N N 2019 Microstructure and mechanical properties of welding–braze welding of Ti/Al butt joints with laser melting deposition layer additive J. Manuf. Process. 38 411–21
[14] Choi J W, Liu H H and Fuji H 2018 Dissimilar friction stir welding of pure Ti and pure Al Mater. Sci. Eng. A 730 168–76
[15] Yao W, Wu A P, Zou G S and Ren J L 2008 Formation process of the bonding joint in Ti/Al diffusion bonding Mater. Sci. Eng. A 480 456–63
[16] Ren J W, Li J and Feng T 2002 Microstructure characteristics in the interface zone of Ti/Al diffusion bonding Mater. Lett. 56 647–52
[17] Li B, Shen Y F, Luo L and Hu W Y 2016 Effects of processing variables and heat treatments on Al/Ti-6Al-4V interface microstructure of bimetal clad-plate fabricated via a novel route employing friction stir lap welding J. Alloys Compd. 658 904–13
[18] Huang Y X, Lv Z L, Lan W, Shen J and dos Santos J F 2017 A new method of hybrid friction stir welding assisted by friction surfacing for joining dissimilar Ti/Al alloy Mater. Lett. 207 172–7
[19] Song X G, Ben D Y, Hu S F, Feng J C and Tang D Y 2017 Vacuum brazing high Nb-containing TiAl alloy to Ti60 alloy using Ti-28Ni eutectic brazing alloy J. Alloys Compd. 692 485–91
[20] Shuie R K, Wu S K, Chen Y T and Shuie C Y 2008 Infrared brazing of Ti50Al50 and Ti–6Al–4V using two Ti-based filler metals Intermetallics 16 1083–9
[21] Li Y, Zhang Y, Bi L and Luo Z 2015 Impact of electromagnetic stirring upon weld quality of Al/Ti dissimilar materials resistance spot welding Mater. Des. 83 577–86
[22] Plaine A H, Gonzalez A R, Suhuddin O F H, dos Santos J F and Alcantara N G 2013 The optimization of friction spot welding process parameters in AA6181-T4 and Ti6Al4V dissimilar joints Mater. Des. 83 36–41
[23] Yuan R, Deng S J, Cui F C, Chen Y X and Lu G 2019 Interface characterization and mechanical properties of dual beam laser welding-brazing Al/steel dissimilar metals J. Manuf. Process. 40 37–45
[24] Huang Y G, Liang G X, Lv M, Al-Nehari M, Liu D G, Li G and Xiao C 2019 Comparative study on the joining performance of TiH2 and ZrH2 modified AgCuZn brazing alloys with pulsed laser welding-brazing J. Manuf. Process 41 56–65
[25] Zhao X Y, Tan C W, Xiao L Y, Xia H B, Chen B, Song X G, Li L Q and Feng J C 2018 Effect of the Ni coating thickness on laser welding-brazing of Mg/steel J. Alloys Compd. 769 1042–58
[26] Zhang Y F, Huang J H, Ye Z, Cheng Z, Yang J and Chen S H 2018 Influence of welding parameters on the IMCs and the mechanical properties of Ti/Al butt joints welded by MIG/TIG double-sided arc welding-brazing J. Alloys Compd. 747 764–71
[27] Wang H D, Yuan X J, Li T, Wu K L, Sun Y Q and Xu C 2018 TiG welding-brazing of TiAlH4 and Al5052 in overlap configuration with assistance of zinc foil J. Mater. Process. Technol. 251 26–36
[28] Dharmendra C, Rao K P, Wilden J and Reich S 2011 Study on laser welding-brazing of zinc coated steel to aluminum alloy with a zinc based filler Mater. Sci. Eng. A 528 1497–503
[29] Li L Q, Tan C W, Chen Y B, Guo W and Hu X B 2012 Influence of Zn coating on interfacial reactions and mechanical properties during laser welding-brazing of Mg to Steel Metall. Mater Trans A 43 4740–54