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Influence of Pulse-Impact on Microstructure of Welded Joints at Various Temperatures in Liquid-Phase-Pulse-Impact Diffusion Welding Particle Reinforcement Aluminum Matrix Composites

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1. Introduction

The high specific strength, good wear-ability and corrosion resistance of Aluminum Matrix Composites (AMCs) attract substantial industrial applications. Typically, AMCs are currently used widely in automobile and aerospace industries, structural components, and heat resistant-wearable parts in engines, *etc.* (Go´mez de Salazar JM et al., 2003; Loyd DJ, 1994; Nair SV et al., 1995; Pirondi A et al., 2009; Rotundo F et al., 2010). The particles of reinforcement elements in AMCs may be either in form of particulates or as short fibers, whiskers and so forth (Loyd DJ, 1994; Maity J et al., 2009). These discontinuous natures create several problems to their joining techniques for acquiring their high strength and good quality weld-joints. Typical quality problems of those welding techniques currently available for joining AMCs (American Welding Society, 1996; Arik H et al., 2005; Feng AH et al., 2008; Fernandez GJ et al., 2004; Hsu CJ et al., 2005; Marzoli LM et al., 2006; Schell JSU et al., 2009; Shanmuga Sundaram N et al., 2010; Wert JA, 2003) are as elaborated below.

1. The distribution of particulate reinforcements in the weld

As properties of welded joints are usually influenced directly by the distribution of particulate reinforcements in the weld, their uniform distribution in the weld is likely to give tensile strength higher than 70~80 % of the parent AMCs. Conglomeration distribution or absence (*viz.* no-reinforcements-zone) of the particulate reinforcements in the weld generally degrades markedly the joint properties and subsequently resulted in the failure of welding.

2. The interface between the particulate reinforcements and aluminum matrix

High welding temperature in the fusion welding methods (typically: TIG, laser welding, electron beam etc.) is likely to yield pernicious Al_4C_3 phase in the interface. Long welding time (e.g. several days in certain occasions) in the solid-state welding methods (such as diffusion welding) normally leads to (i) low efficiency and (ii) formation of harmful and brittle intermetallic compounds in the interface.

To alleviate these problems incurred by the available welding processes for welding AMCs, a liquid-phase-pulse-impact diffusion welding (LPPIDW) technique has been developed (Guo W et al., 2007; Guo W et al., 2008; Guo W et al., 2008). This paper aims at providing some specifically studies the influence of pulse-impact on the microstructures of welded joints. Analysis by means of scanning electron microscope (SEM), transmission electron microscope (TEM) and X-Ray Diffraction (XRD) allows the micro-viewpoint of the effect of pulse-impact on LPPIDW to be explored in more detail.

2. Experimental material and process

2.1 Specimens

Stir-cast $\text{SiC}_p/\text{A356}$, P/M $\text{SiC}_p/6061\text{Al}$ and $\text{Al}_2\text{O}_{3p}/6061\text{Al}$ aluminum matrix composite, reinforced with 20 %, 15 % volume fraction SiC , Al_2O_3 particulate of 12 μm , 5 μm mean size, are illustrated in Figs. 1~ 3.

2.2 Experiment



Fig. 1. Microstructure of aluminum matrix composite $\text{SiC}_p/\text{A356}$

The quench-hardened layer and oxides, as induced by wire-cut process, on the surfaces of aluminum matrix composite specimens were removed by careful polishing using 400 # grinding paper. The polished specimens were then properly cleaned by acetone and pure ethyl alcohol so as to remove any contaminants off its surfaces. A DSI Gleeble®-1500D thermal/mechanical simulator with a 4×10^{-1} Pa vacuum chamber was subsequently used to perform the welding.

The microstructures and the interface between the reinforcement particle and the matrix of the welded joints were analyzed by SEM and TEM.

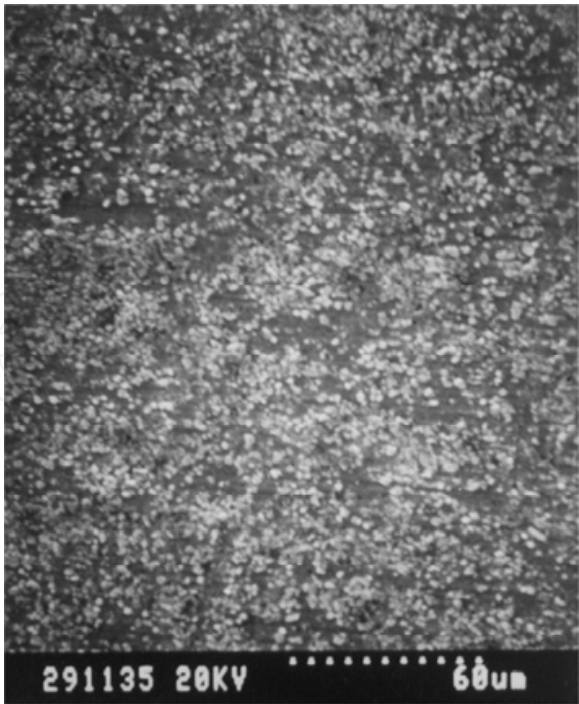


Fig. 2. Microstructure of aluminum matrix composite SiC_p/6061Al

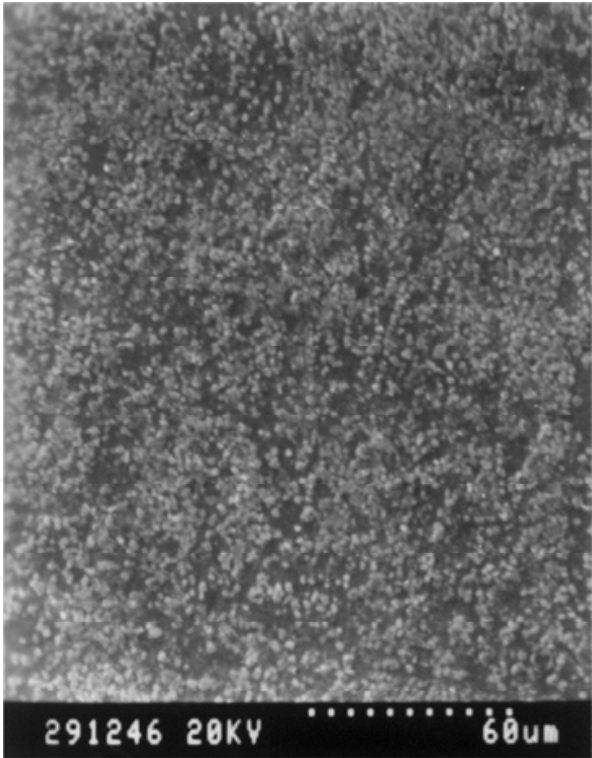


Fig. 3. Microstructure of aluminum matrix composite Al₂O_{3p}/6061Al

2.3 Operation of LPPIDW

Figure 4 illustrates a typical temperature and welding time cycle of a LPPIDW. It basically involved with: (i) an initially rapid increase of weld specimens, within a time of t_a , to an

optimal temperature T_a at which heat was preserved constantly at T_a for a period of $(t_b - t_a)$, (ii) at time t_c , a quick application of pulse impact to compress the welding specimens so as to accomplish an anticipated deformation δ within a glimpse of $10^{-4} \sim 10^{-2}$ s, whilst the heat preservation was still maintained at the operational temperature T_a ; and (iii) a period of natural cooling to room temperature after time t_b .

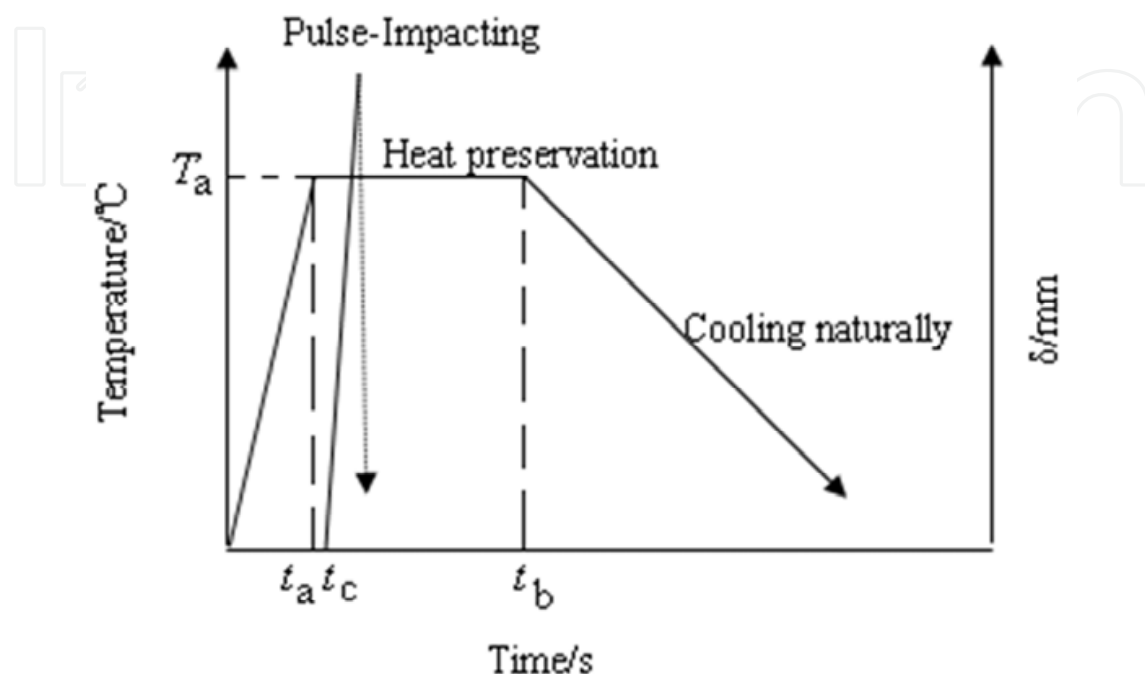


Fig. 4. Schematic diagram of liquid-phase-pulse-impact diffusion welding

3. Results and discussion

3.1 Microstructure of welded joint

Figure 5 shows the microstructures of welded joints of $\text{SiC}_p/\text{A356}$ at various temperatures with $V_I=560$ mm/s, $t_I=10^{-2} \sim 10^{-4}$ s, $t=30$ s, $P_0=5$ MPa, $\delta=1$ mm, where V_I was velocity of pulse-impact, t_I was the impacting time, t was holding time for heat preservation, P_0 was holding pressure during the welding, δ was the horizontal deformation. It elucidated that when the welding temperature was 563°C , under the effect of pulse-impact, the liquid phase matrix alloy wasn't formed enough to wet the particle reinforcements. In addition, at this temperature, the diffusion capability of the atoms within the matrix was relatively low. As a result, the welding interface between two specimens could be observed obviously as shown in Fig. 5(a) and followed by the unsuitable strength (about 118 MPa). Moreover, because of lower welding temperature, the area of the formed solid-liquid phase was smaller, which led to some streamlines scattered in the matrix (Fig. 5(a)) after the pulse-impact acting on the substrates. When the temperature reached 565°C , the rate of the atom diffusion in the joint region within the matrix was accelerated (Fig. 5(b)). At the same time, more liquid phase matrix alloy was formed to wet reinforcements (SiC). Therefore, the interface state of reinforcement and reinforcement was improved and the reinforcements were distributed uniformly to some extent. Also, the streamlines scattered in the matrix were disappeared, and the tensile strength of welded joints was about 134 MPa higher than that of 563°C .

When the temperature is up to 570 °C, the formed liquid phase matrix alloy was enough and suitable for wetting reinforcements effectively, and the rate of the atom diffusion was more active. As a result, for reinforcements the welding mode in the joint region changed from reinforcement - reinforcement to reinforcement - matrix - reinforcement. Consequently, the joint was welded successfully (Fig. 5(c)). The average strength of 179 MPa for the welded joints produced at welding temperature of 570 °C was about 74.6 % of the 240 MPa for the strength of parent aluminum matrix composite.

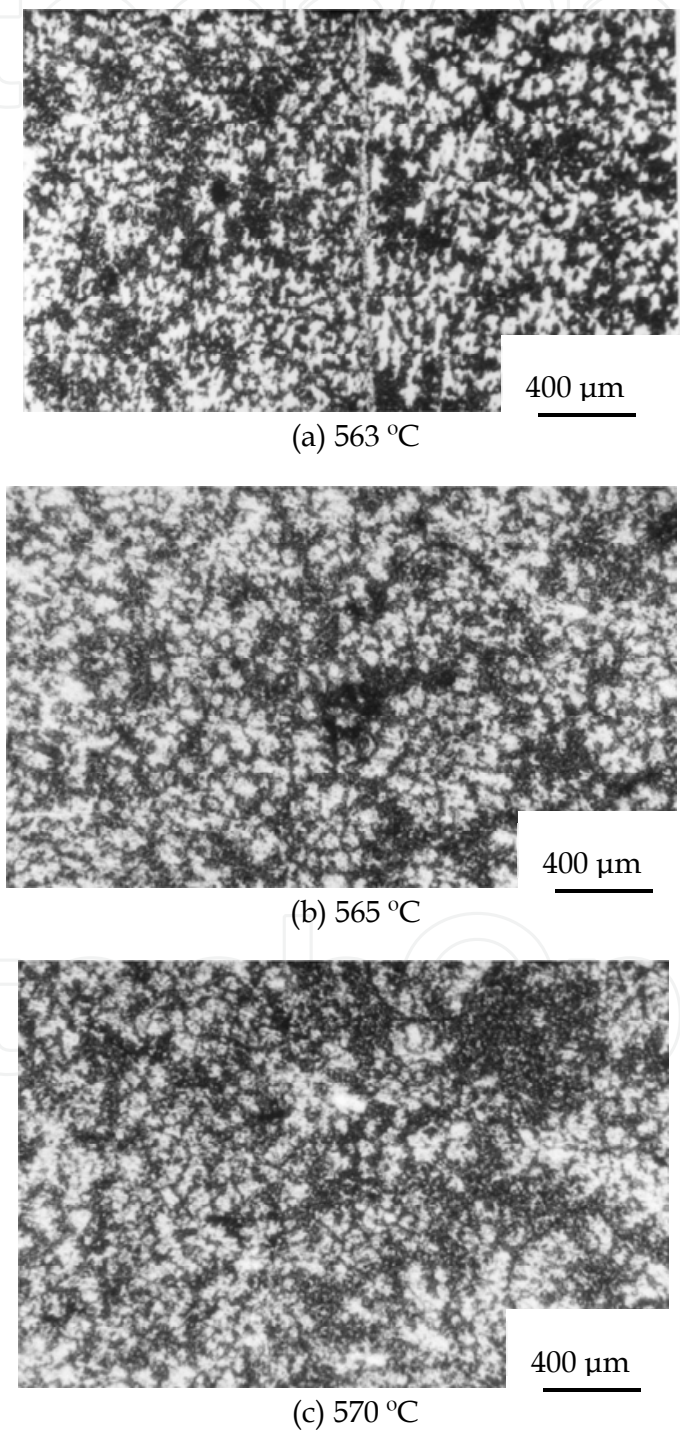
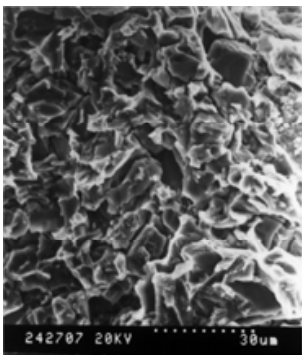


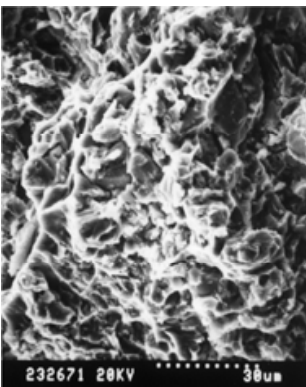
Fig. 5. Microstructures of welded joints of SiC_p/A356 at various temperatures by LPPIDW



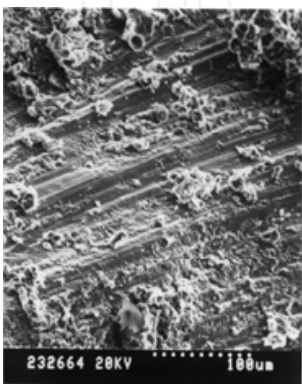
(a) 563 °C



(b) 565 °C



(c) 570 °C



(d) 575 °C

Fig. 6. Fractographs of SiC_p/ A356 at various temperatures

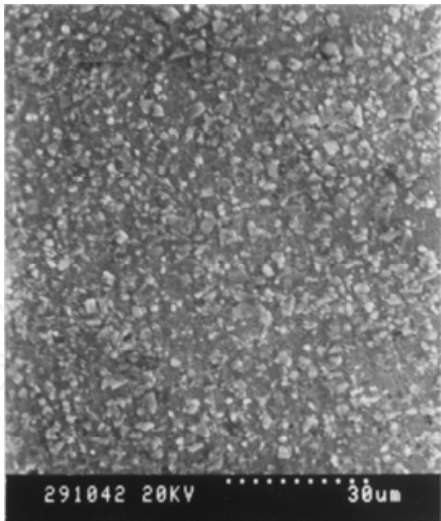
The relevant fractographs are shown in Fig. 6. It illustrated that when the welding temperature was 563 °C, the initial morphology of substrate could be detected obviously, and some sporadic welded locations appeared together with some rather densely scattering bare reinforcement particles as shown in Fig. 6(a). With the welding temperature was increased to 565 °C, more liquid phase was formed. Under the effect of pulse-impact, some wet locations in the joint had been excellently welded and the aggregated solid reinforcement particles were improved. However, the bare reinforcement particles were still distributed on the fractographic surface. It indicated that substrates did not weld ideally the pieces together and it consequently resulted in a low strength joint (Fig. 6(b)). Figure 6(c) shows the fractograph of welded joint at 570 °C. It illustrated that the fracture was dimple fracture. Moreover, SEM of the fracture surface showed some reinforcement particles (SiC) in the dimple. In order to confirm the state of these reinforcement particles, particles itself and matrix neighboring to these particles were analyzed by energy dispersive X-ray analysis (EDX) respectively. It indicated that reinforcement particles (SiC) were wet by matrix alloy successfully suggesting that the reinforcement particles had been perfectly wet and the composite structure of reinforcement/reinforcement had been changed to the state of reinforcement/matrix /reinforcement.

As welding temperature increasing to 575 °C, it led to more and more liquid phase matrix alloy distributing in the welded interface, meanwhile, more liquid phase matrix alloy reduced the effect of impact on the interface of the welded joints, subsequently the application of transient pulse-impacting would cause the relative sliding of the weldpieces that jeopardized ultimately the formation of proper joint as shown in Fig. 6(d). It demonstrated that results of fractographs were agreed with the corresponding microstructures well.

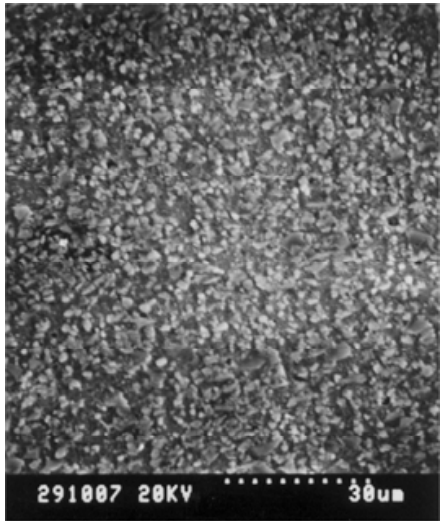
The relevant results of SiC_p/6061Al and Al₂O_{3p}/6061Al at various welding temperatures are shown in Fig. 7 to Fig. 10.

It showed that the microstructure evolutions and its corresponding fracture surfaces under the effect of pulse-impact are similar to that of SiC_p/A356.

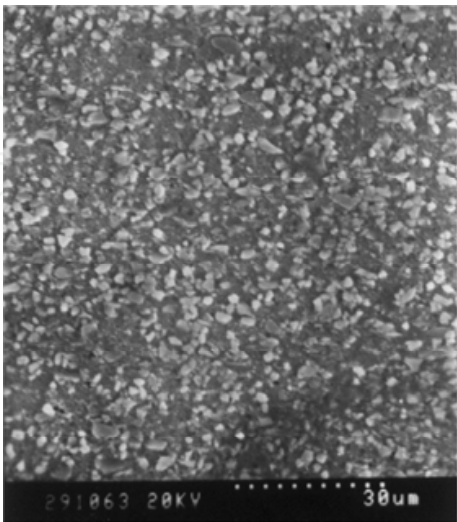
Figures 7(a) and 9(a) show when the welding temperature was too low to form enough liquid phase matrix alloy to wet the reinforcement particles, and the diffusion capability of the atoms within the matrix was relatively low. Therefore, the indistinct welding interface between two specimens could be observed resulted in low tensile strength (about 240 MPa for SiC_p/6061Al and 270MPa for Al₂O_{3p}/6061Al). When the temperature is higher (623 °C for SiC_p/6061Al and 644 °C for Al₂O_{3p}/6061Al), the liquid phase matrix alloy was formed enough to wet the reinforcement particles (SiC), together with higher rate of the atom diffusion in the joint region (Figs. 7(b) and 9(b)). Consequently, the joints could be welded successfully with the average strength of 260 MPa for SiC_p/6061Al (about 72.2 % of the 360 MPa for the strength of parent aluminum matrix composite) and 282 MPa for Al₂O_{3p}/6061Al (about 70.5 % of the 400 MPa for the strength of parent aluminum matrix composite). As welding temperature increasing further (such as 625 °C for SiC_p/6061Al and 647 °C for Al₂O_{3p}/6061Al), more and more liquid phase matrix alloy would be distributed in the welded interface, at the same time, more liquid phase matrix alloy reduced the effect of impact on the interface of the welded joints, subsequently prompted for the descending of the joint strength (Figs. 7(c) and 9(c)).



(a) 620 °C

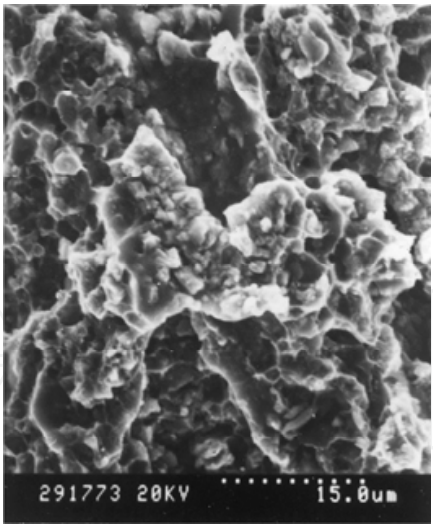


(b) 623 °C

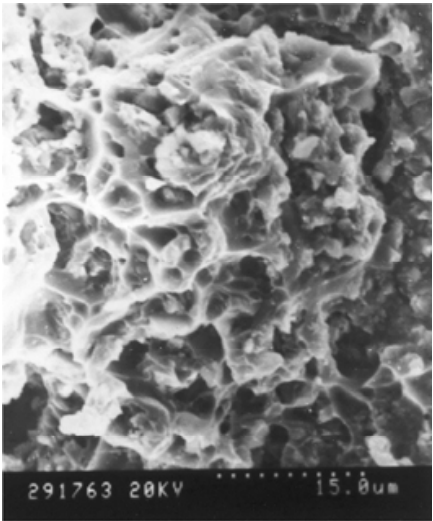


(c) 625 °C

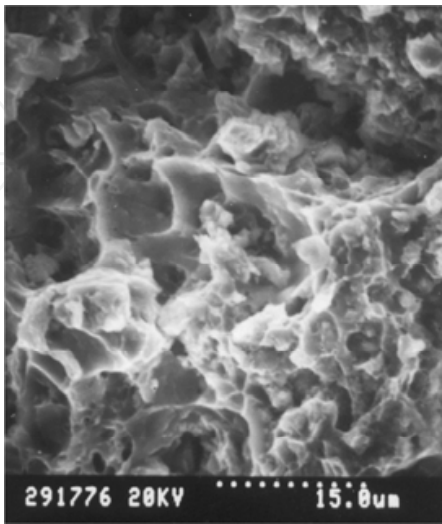
Fig. 7. SEM micrographs of SiC_p/6061Al welded joints at various welding temperatures



(a) 620 °C

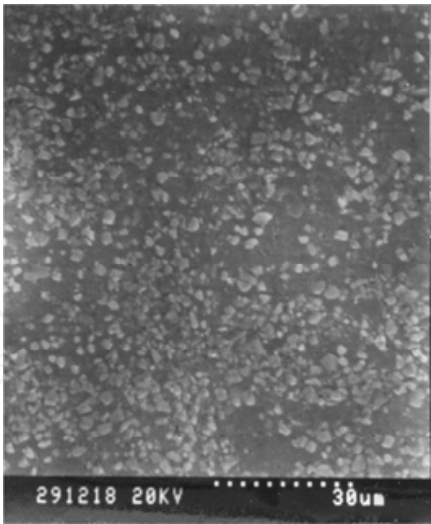


(b) 623 °C

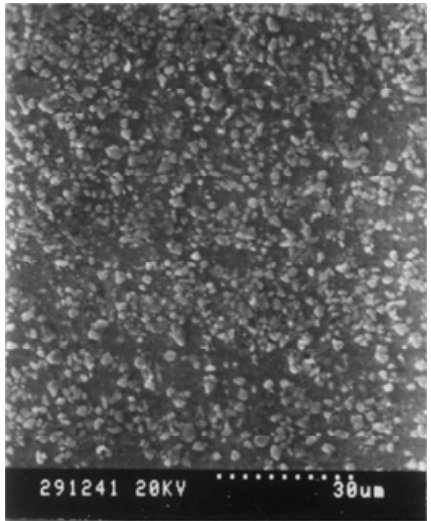


(c) 625 °C

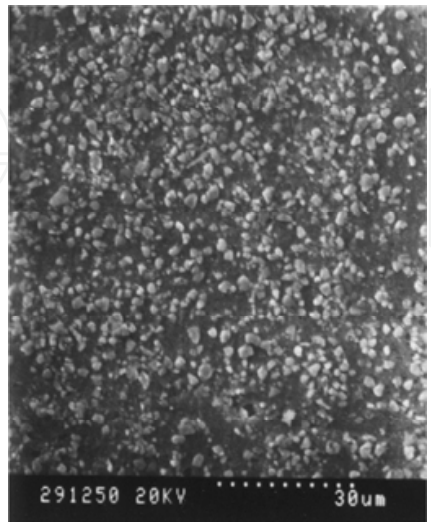
Fig. 8. Fractographs of SiC_p/6061Al at various temperatures



(a) 641 °C

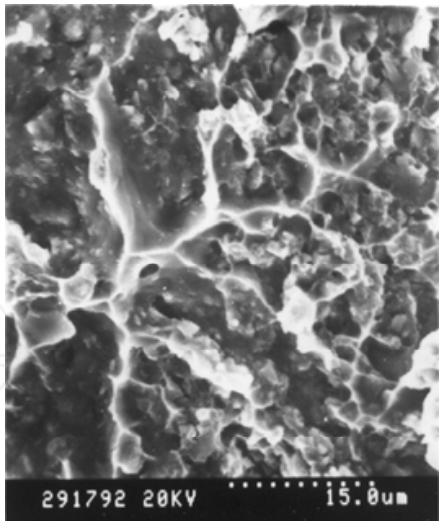


(b) 644 °C

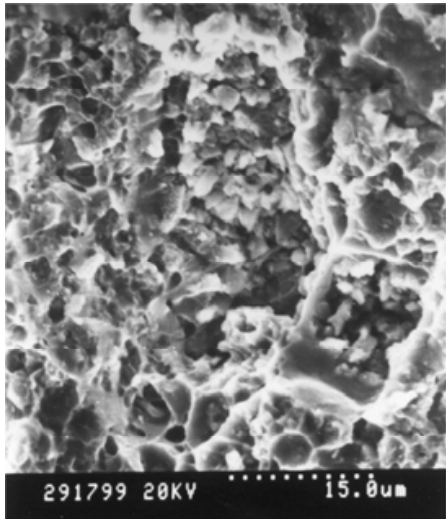


(c) 647 °C

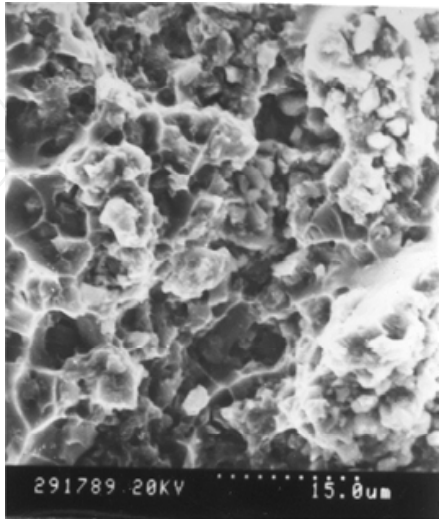
Fig. 9. SEM micrographs of Al₂O_{3p}/6061Al welded joints at various welding temperatures



(a) 641 °C



(b) 644 °C



(c) 647 °C

Fig. 10. Fractographs of Al₂O₃_p/6061Al at various temperatures

Moreover, according to the fractures of welded joints at various temperatures shown in Figs. 8 and 10, it showed that it agreed with Figs. 7 and 9 very well, and the fractures were all dimple fractures with some reinforcement particles (SiC, Al₂O₃) in the dimple. Also, the results of SiCp/6061Al were better than that of Al₂O₃p/6061Al due to a mild interfacial reaction between the reinforcement and matrix, which released the thermal mismatch stress to an acceptable extent between the reinforcement and matrix to allow load transfer from the matrix to reinforcement successfully. As a result, it had advantageous effect of improving the strength of welded joints further (Guo W et al., 2008).

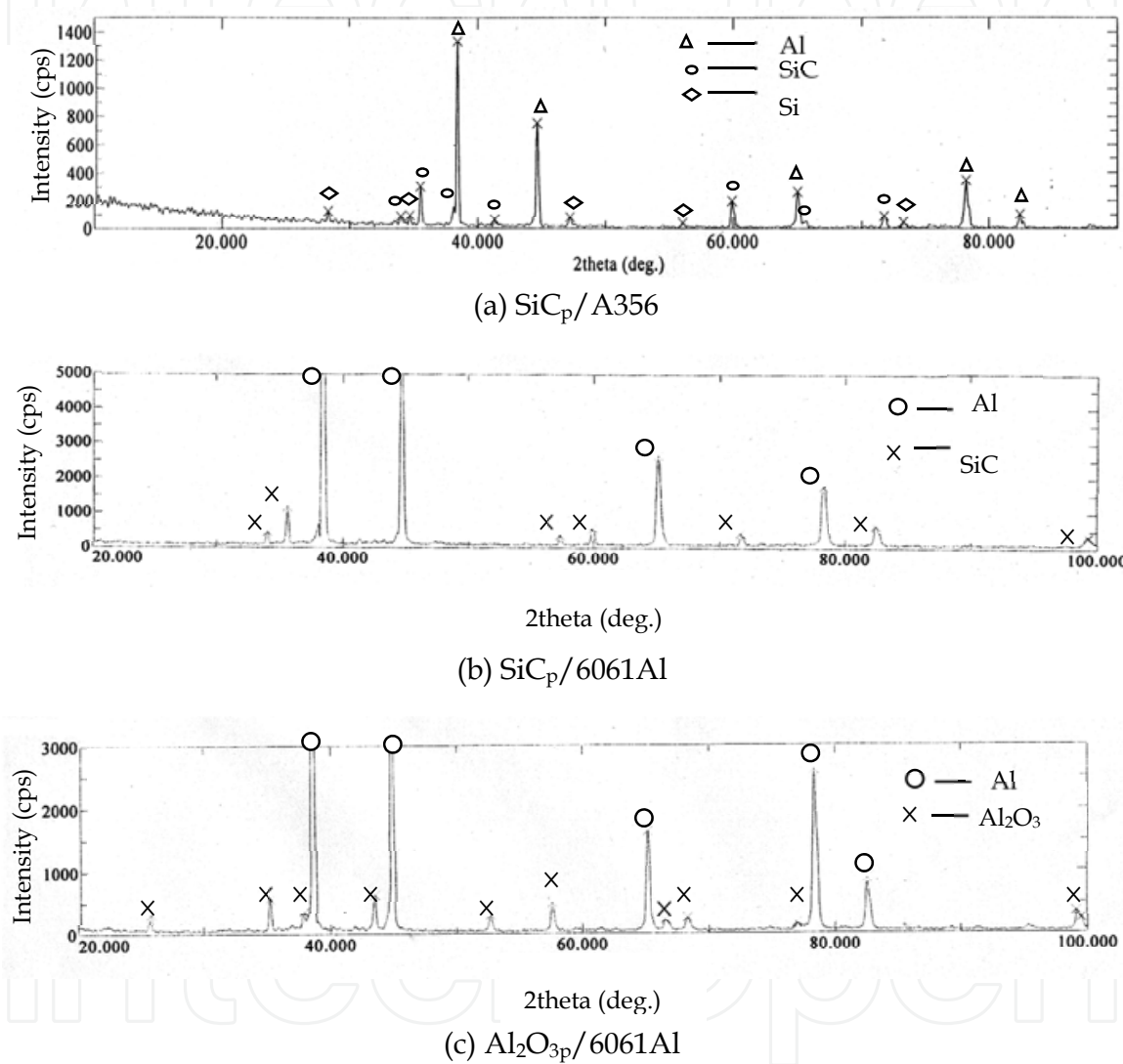


Fig. 11. XRD pattern of the fracture surfaces

Based on microstructures of the welded joints with the optimal parameters (i.e., $T_{\text{SiCp/A356}}=570\text{ }^{\circ}\text{C}$, $T_{\text{SiCp/6061Al}}=623\text{ }^{\circ}\text{C}$, $T_{\text{Al}_2\text{O}_3\text{p}}=644\text{ }^{\circ}\text{C}$, $V_f=560\text{ mm/s}$, $t_f=10^{-2}\sim 10^{-4}\text{ s}$, $\delta=1\text{ mm}$, $t=30\text{ s}$, $P_0=5\text{ MPa}$) and its corresponding fracture surfaces as shown in Figs. 5, 6, 7-10, the welded joint displayed with uniformly distributing reinforcement particles and microstructure almost similar to that of its parent composite (Figs. 1, 2 and 3). SEM of the fracture surface showed that the reinforcement particles had been perfectly wet and the composite structure of reinforcement/reinforcement had been changed to the state of reinforcement/matrix/reinforcement. XRD pattern of the fracture surfaces (Fig. 11) did not illustrate the existence of

any harmful phase or brittle phase of Al_4C_3 . This suggested the effective interface transfers between reinforcement particles and matrix in the welded joint that subsequently provided favorable welding strength (Guo W et al., 2007; Guo W et al., 2008; Guo W et al., 2008).

3.2 Distribution of dislocation in the welded joint

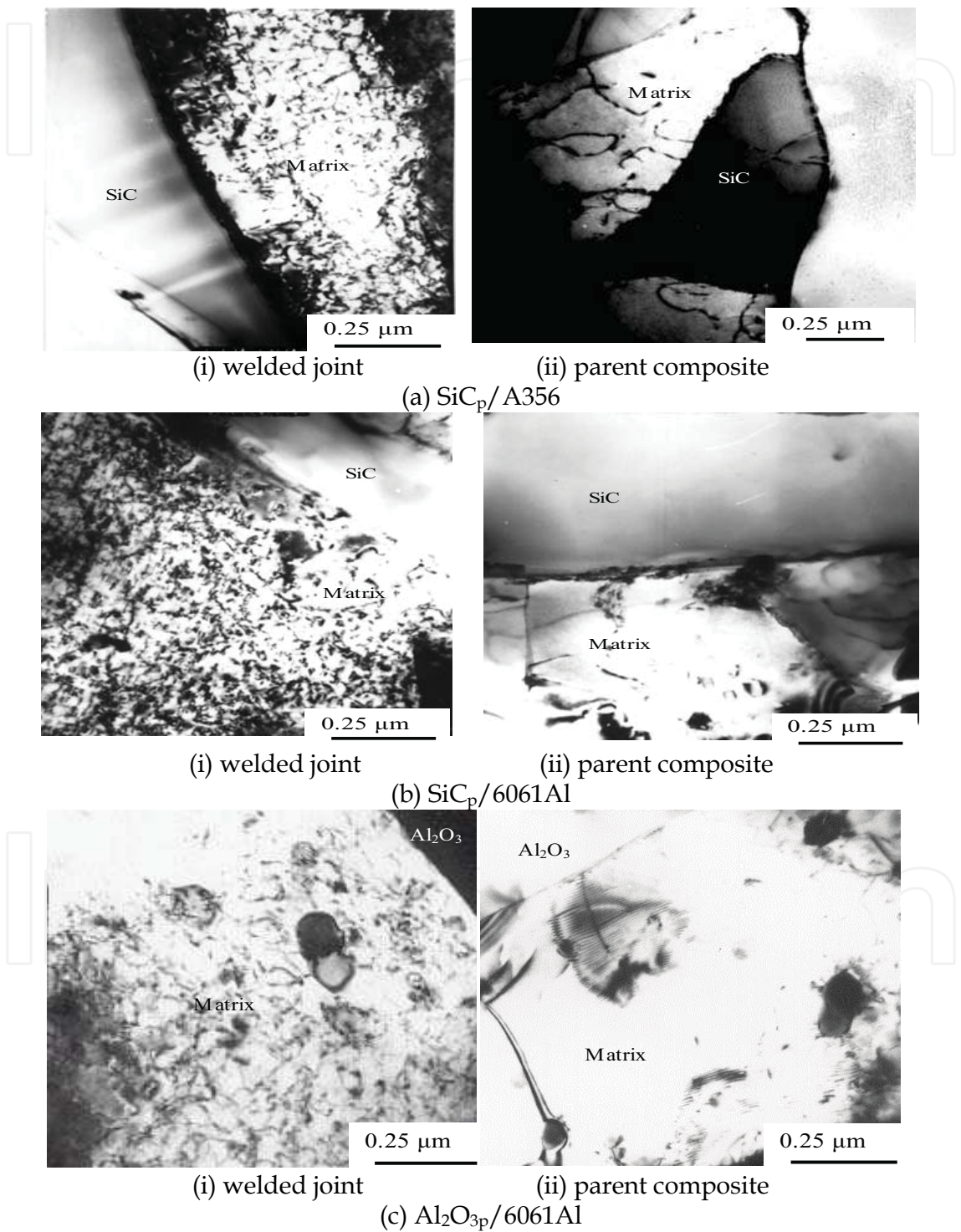


Fig. 12. Distribution of dislocation in the matrix neighboring to the interface of the welded joint and parent composite respectively

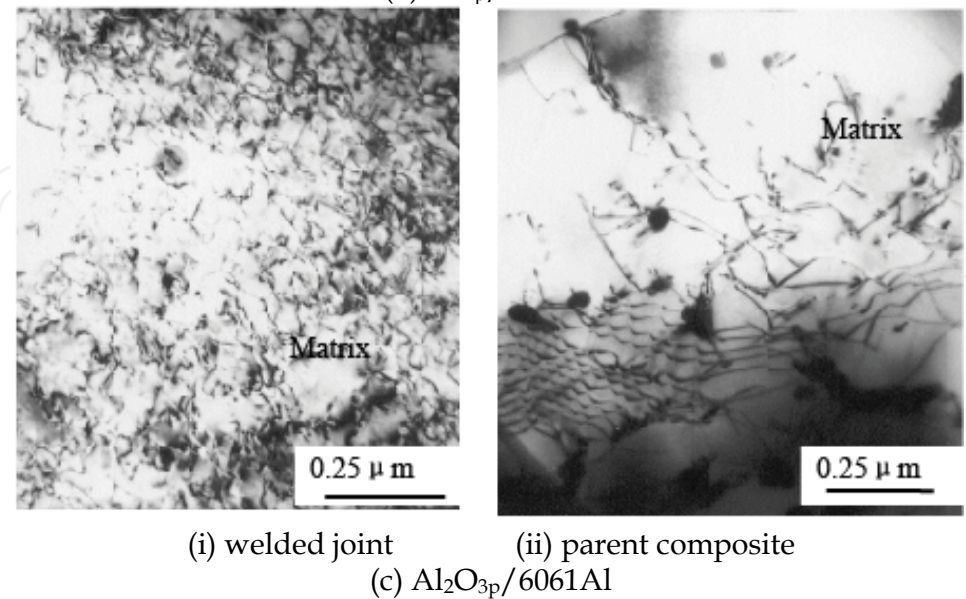
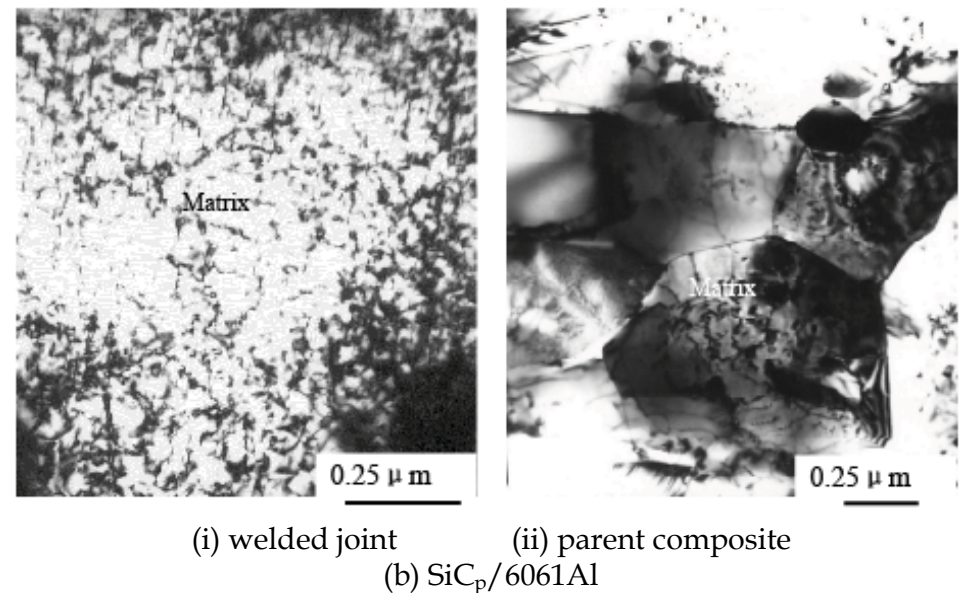
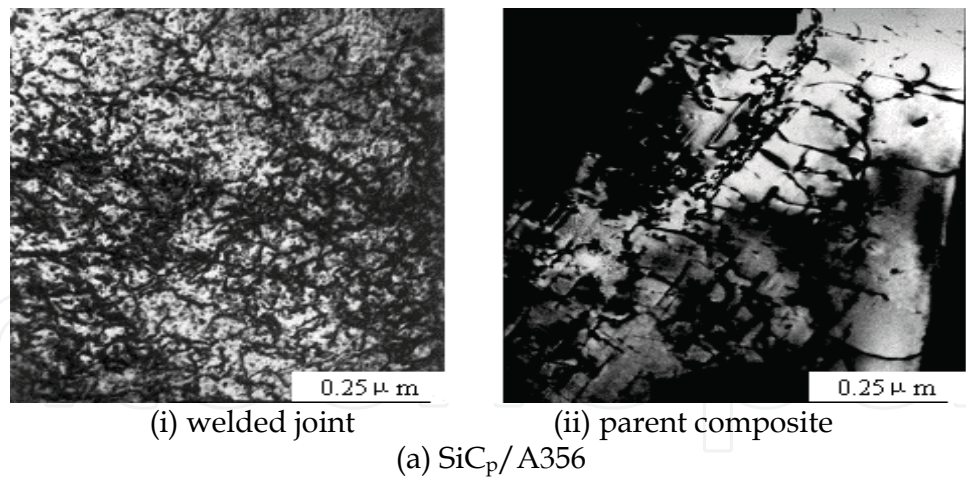


Fig. 13. Distribution of dislocation in the matrix away from the interface of the welded joint and parent composite respectively

The distribution of dislocation in the matrix neighboring to the interface of the welded joint by LPPIDW in comparison with its parent composite is shown in Fig. 12. The clearly distinctive interface between reinforcement particle and matrix indicated that the integration between the reinforcement particle and matrix was prominent. The effect of pulse-impact subsequently led to dislocation in the matrix lattices and showed sign of mutually entwisting to give higher welded strength. Comparatively, its dislocation distribution in the matrix neighboring to the interface was relatively denser than that in its parent composite (cf. Figs. 12(i) and 12(ii)). Similarly, the density of dislocation and dislocation entwisting in the matrix away from the welded interface was also higher than that of its parent composite (cf. Figs. 13(i) and 13(ii)). Such favorable characteristics ultimately gave relatively superior strength of the welded joint to that of conventional diffusion welding (Guo W et al., 2007; Guo W et al., 2008; Guo W et al., 2008).

3.3 Formation of nano-grains in the weld

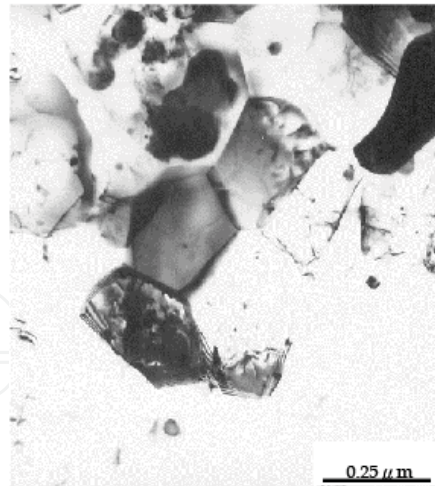


(a) SiC_p/A356



(b) SiC_p/6061Al

Fig. 14. (a,b) Nano-grains formed in the weld of particle reinforcement aluminum matrix composites during the LPPIDW.



(c) $\text{Al}_2\text{O}_{3\text{p}}/\text{6061Al}$

Fig. 14. (c) Nano-grains formed in the weld of particle reinforcement aluminum matrix composites during the LPPIDW. (Continuation)

TEM micrograph (Fig. 14) of a weld by LPPIDW displayed some newly-formed nano-grains in the lattices of the joint. These nano-grains would seat in the interstices of crystal lattices and create new grain boundary in hindering the movement of neighbouring grains and subsequently improved obviously the properties of the welded joints. The formation of new nano-grains was the advantageous effect of pulse-impact in LPPIDW. In addition, XRD pattern of the fracture surface (Fig. 11) did not illustrate the existence of any harmful phase or brittle phase of Al_4C_3 . This suggested the effective interface transfers between reinforcement particles and matrix in the welded joint that subsequently provided favorable welding strength (Guo W et al., 2007; Guo W et al., 2008; Guo W et al., 2008).

4. Conclusions

Results of this study on the microstructures of welded joints of particle reinforcement aluminum matrix composites ($\text{SiC}_\text{p}/\text{A356}$, $\text{SiC}_\text{p}/\text{6061Al}$, $\text{Al}_2\text{O}_{3\text{p}}/\text{6061Al}$) using liquid-phase-pulse-impact diffusion welding process show that:

1. Pulse-impact in liquid-phase-pulse-impact diffusion welding in joining particle reinforcement aluminum matrix composites ($\text{SiC}_\text{p}/\text{A356}$, $\text{SiC}_\text{p}/\text{6061Al}$, $\text{Al}_2\text{O}_{3\text{p}}/\text{6061Al}$) resulted in higher density of dislocation in the matrix neighboring to and away from the interface than their parent composite. Simultaneously, the dislocation entwisted mutually and intensively in the welded joint propitious to improve the strength of welded joints.
2. There was distinctly clear interface between reinforcement particle and matrix. It overcame some diffusion problems normally encountered in conventional diffusion welding, and prevented the formation of harmful microstructure or brittle phase in the welded joint.
3. The joint by LPPIDW process would form nano-grains. The newly-formed nano-grains would improve the properties of welded joints resulted in higher tensile strength.

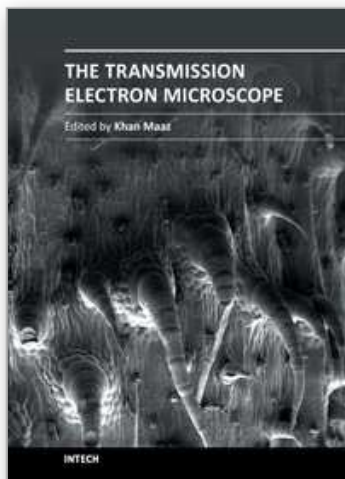
5. Acknowledgement

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The Transmission Electron Microscope

Edited by Dr. Khan Maaz

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The book "The Transmission Electron Microscope" contains a collection of research articles submitted by engineers and scientists to present an overview of different aspects of TEM from the basic mechanisms and diagnosis to the latest advancements in the field. The book presents descriptions of electron microscopy, models for improved sample sizing and handling, new methods of image projection, and experimental methodologies for nanomaterials studies. The selection of chapters focuses on transmission electron microscopy used in material characterization, with special emphasis on both the theoretical and experimental aspect of modern electron microscopy techniques. I believe that a broad range of readers, such as students, scientists and engineers will benefit from this book.

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