

Ultrasonic welding of dissimilar materials: A review

Elma KICUKOV, Ali GURSEL

International University of Sarajevo

Department of Mechanical Engineering

Sarajevo, Bosnia and Herzegovina

Abstract

During the last few years ultrasonic welding has become significant attention regarding its suitable applications in comparison to traditional welding techniques. Bonding of dissimilar materials has always been a challenging task due to poor control on grain size and sensitive mechanical properties that could have been made by joining with traditional welding techniques. Moreover, joining dissimilar materials such as Aluminum/steel, metal/glass, Aluminum/copper had not been achieved without the usage of ultrasonic welding technique. This work presents a review of literature regarding the usage of ultrasonic welding technique in many applications. Additionally, this paper provides different examples and applications of ultrasonic welding technique and its application. Main advantages of this technique are, clean and undamaged exterior parts of weld, power savings, stable and strong bond, time efficiency

Keywords: ultrasonic welding (USW), dissimilar materials

1. Introduction

Ultrasonic welding is a joining process where high frequency vibrations are produced and converted into energy that is applied on work pieces that are held together under pressure. Energy produced as a product of vibrations is joining pieces of materials together but without melting. Ultrasonic welding provides high quality joint between similar and dissimilar materials. The joint is made in two ways either materials are deformed or diffused and deformed together in order to join them and produce high quality weld. Commonly, polymers are welded with ultrasonic technique, however, dissimilar materials are welded with this technique too. Main reason why

nowadays similar and dissimilar materials are bonded ultrasonically is because it does not damage the base material. Bonding occurs with melting but the melting is not that high to cause breakage of materials. USW is suitable for non-ferrous soft metals and their alloys such as aluminum, copper, brass, silver and gold. [1] However, it is also suitable technique for joining metals such as titanium, nickel and their dissimilar combinations such as Aluminum/steel, metal/ceramic, metal/glass, Aluminum/copper. [2] This paper focuses mainly on the usage of the ultrasonic welding technique for joining dissimilar materials and its applications regarding electronic, aerospace, medical industry and automotive industry.

2. Theoretical background

The ultrasonic welding process consists of five major components: power supply (providing electrical energy at high frequency), piezoelectric transducer (part that converts electrical energy into mechanical vibrations), wedge that amplifies mechanical work, sonotrode (enhances the amplitude of mechanical vibrations), and pneumatic cylinder that provides clamping pressure during welding. [3] In USW two system configurations are used wedge reed and lateral derive. Wedge reed system is more useful for joining of sheets with large thickness due to that anvil acts as vibrating part and resonates out of phase to the reed. Lateral derive system is simple and it gives good results for thin specimens due to its lower rigidity. Main parameters during USW process dependant on each other are vibration amplitude, clamping force, power, frequency, energy and time. Mostly euipment available for USW ranges from 15-75kHz. Nowadays, commonly used is 20 kHz since at this frequency very high strain rates (of order of 10^3 - 10^5 s⁻¹) and strains can be developed in a fraction of a second during the shearing of micron-sized asperities between welded samples. [4]

3. Applications and usage of ultrasonic welding

3.1 Use of ultrasonic welding on $\text{Cu}_{54}\text{Zr}_{22}\text{Ti}_{18}\text{Ni}_6$ bulk metallic glass

A $\text{Cu}_{54}\text{Zr}_{22}\text{Ti}_{18}\text{Ni}_6$ bulk metallic glass has been produced by two proceses by arc

melting and roll melthod that had to be further joined by ultrasonic wleding. A bulk metallic glass of dimension 15mm x 15 mm x 1mm was joined by the by sonotrode that exerts a normal pressure of 80 N with the vibration time from 0.3 s to 4.0 s under constant frequency of 20 kHz. Figure 1 shows the morphologies and microstrucure of work pieces with respect to different vibration times. The cross-section of the work piece of bulk metallic glass is described by upper plate morphology and interfacial morphology. The welded interface is discontinously welded after 0.3 s, thus, the optimum time for welding the bulk metallic glass is 1.0 s for vibration frequency of 20 kHz and exerted normal pressure of 80N. The thickness of upper bulk metallic glass significantly decreased after 1.0 s, and more after 4.0 s. The exerted force has been set constant to be 80 N for all pieces of bulk metallic glass. The morphological change occured due to the change in mechanical properties of the bulk metallic glass workpiece. Heat that was supplied and transferred during ultrasonic welding process increased the temperature and has been transfered to the bulk materials through conduction. Increase in the heat supplied with the respect to time came as a result in increasing the temperature in bulk metallic glass workpiece that lead to its crystalization temperature. The experiment has proven that by using normal pressure of 80N and time duration of vibration of 1 s and frequency of 20kHz has been welded 1 mm thich without any evidence of crystalization. The molecular strucuture

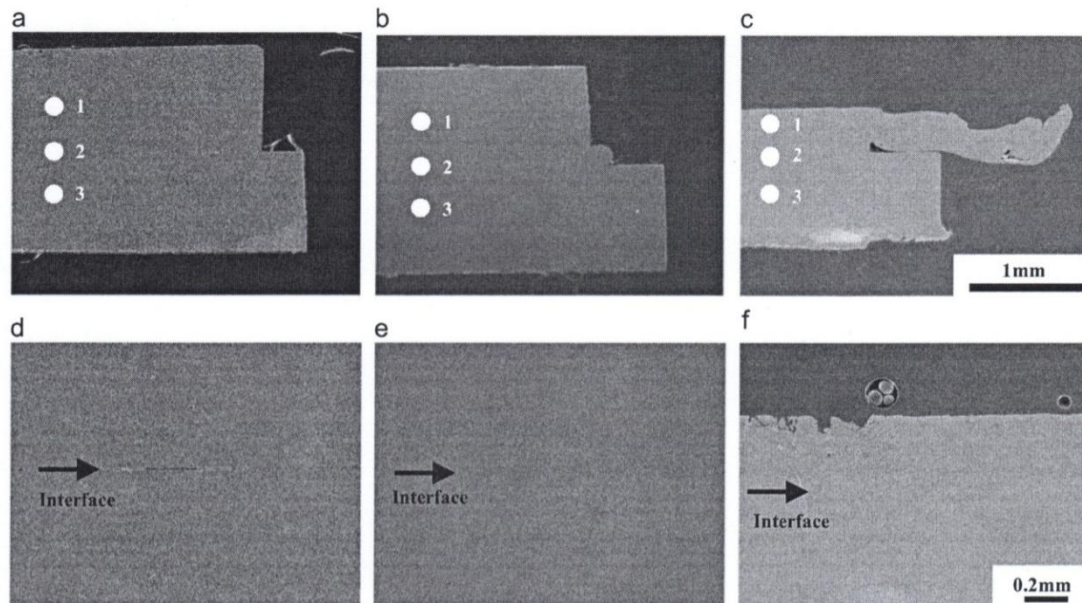


Figure 1: Cross-sectional morphologies and microstructures of joining workpieces with respect to time: (a) and (d) duration of vibration 0.3 s, (b) and (e) duration of vibration is 1.0 s, (c) and (f) is 4.0 s [6]

of the $\text{Cu}_{54}\text{Zr}_{22}\text{Ti}_{18}\text{Ni}_6$ bulk metallic glass has not been changed nor destroyed making it perfectly to be used in terms of developing further nanocomposites for electronic applications. [5]

3.1.1 Use of ultrasonic welding of 3003 Aluminium with 304 Stainless steel alloy

The ultrasonic welding process has been applied between two dissimilar materials 3003 Aluminium alloy of 300 m and Stainless steel alloy foil of 50 m with 2.4 kW ultrasonic device. The experiment included welding tip of 8x6 mm attached to sonotrode as shown in figure 2. The workpieces were cut in length parallel to dimension of 25 x 100 mm² and welded using 25 mm overlapping. Amplitude of vibration was 58 m. Power of the ultrasonic device was 2.4 kW and energy varied in range of 75 to 200J under different pressures. [7]

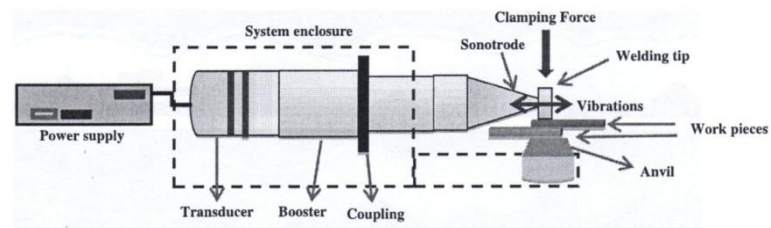


Figure 2: Schematic diagram for ultrasonic welding process device [8]

Figure 3(a) shows the microstructure of 3003 Aluminum. When the ultrasonic process is applied the external side of 3003 Aluminum experiences shear forces. In figure 3(b) the structure is similar to lower weld energy of 75 J. As the energy increased the recrystallization point emergend along the external surface of the 3003 Aluminum as shown in 3(c) and 3(d). The recrystalization apperead due to temperature differences.

To sum up, when the normal pressure of 30 psi was applied the strength of the bond was supplied with energy of 150 J. It has to be pointed out that as the

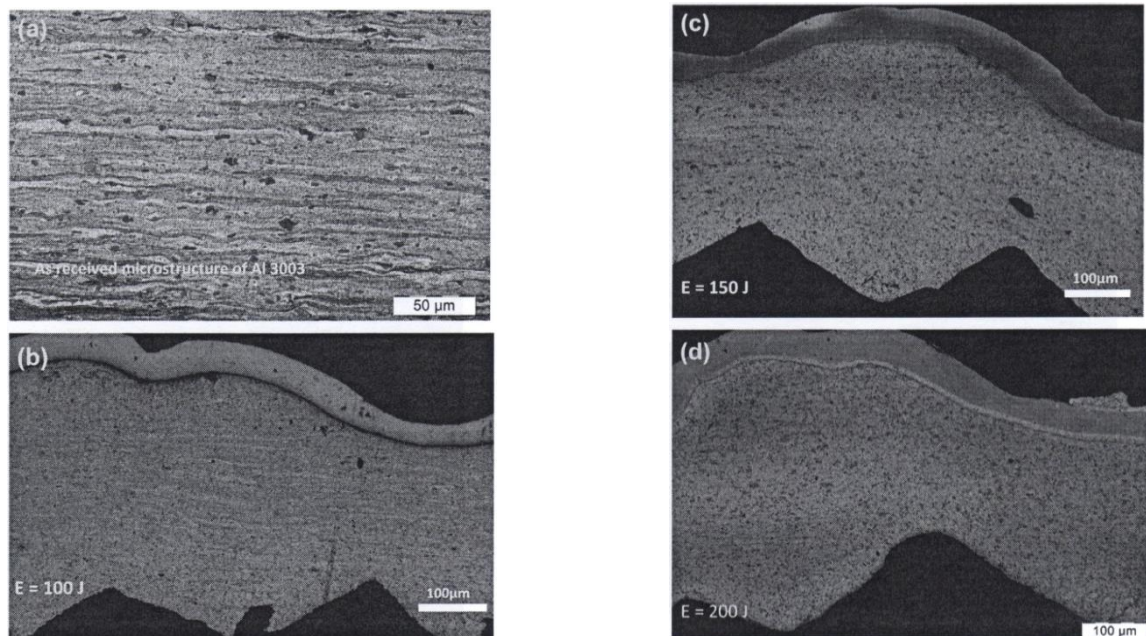


Figure 3: Micrograph showing microstructure with different energies during ultrasonic welding [9]

normal pressure increases the strength of the weld can be successfully achieved at lower energy in shorter time period. Moreover, as the energy of welding increases thus the microstructure dissipated and the weld recrystallized due to temperature differences. Additionally, the welding process performed with 125 J and 150 J energy shows the maximum tensile load and is characterized as a good weld as shown in. The good quality weld with maximum tensile strength is achieved as a result of corresponding bond density is achieved. [10]

3.2 Ultrasonic welding of Al/Mg/Al tri layered clad sheets

Lightweighting has been regarded as a key strategy in the automotive and aerospace industries to improve fuel efficiency and reduce anthropogenic environment-damaging, climate-changing, human death-causing and costly emissions. [11-16] It has been reported that the fuel efficiency of passenger vehicles can be enhanced by

6–8% for each 10% reduction in weight [17]. Magnesium (Mg) alloy, as the lightest structural metallic material with a density of 30% less than aluminum and one fourth of steel, has been increasingly used in the transportation industry to reduce the weight of motor vehicles [11,12,18–22]. However, the concerns about poor corrosion resistance and low room-temperature formability of Mg alloys limit a widespread structural application in transportation industry [13–23]. Recently, roll cladding has been identified as a promising technique to improve the corrosion resistance and formability of Mg alloys [24–31]. In particular, Al-clad Mg alloy sheet can combine the corrosion resistance and formability of an Al alloy with the high strength-to-weight ratio of Mg substrate. Several studies have shown the successful cladding of Al on Mg alloy sheet using hot and cold rolling, which resulted in good surface corrosion resistance and improved formability [24,25,32].

Additionally, ultrasonic welding (USW) can be used to join Al/Mg/Al tri-layered clad sheets, in order to investigate weldability and identifying failure mode in relation to the welding energy. It was observed that the application of a low welding energy of 100 J was able to achieve the optimal welding condition during USW at a very short welding time of 0.1 s for the tri-layered clad sheets. The optimal lap shear failure load obtained was equivalent to that of the as-received Al/Mg/Al tri-layered clad sheets. With increasing welding energy, the lap shear failure load initially increased and then decreased after reaching a maximum value. At a welding energy of 25 J, failure occurred in the mode of interfacial failure along the center Al/Al weld interface due to insufficient bonding. At a welding energy of 50 J, 75 J and 100 J, failure was also characterized by the interfacial failure mode, but it occurred along the Al/Mg clad interface rather than the center Al/Al weld interface, suggesting stronger bonding of the Al/Al weld interface than that of the Al/Mg clad interface. The overall weld strength of the Al/Mg/Al tri-layered clad sheets was thus governed by the Al/Mg clad interface strength. At a welding energy of 125 J and 150 J, thinning of weld nugget and extensive deformation at the edge of welding tip caused failure at the edge of nugget region, leading to a lower lap shear failure load.

All in all, the resistance heat assisted ultrasonic welding technique (RUSW) were used. RUSW of 6061 aluminum to pure copper was investigated via comparison with the ultrasonic welding

(USW) process when holding the welding parameters constant. The following conclusions were drawn:

1. Due to the synergistic effects of the ultrasonic energy and resistance heat, the peak power of ultrasonic vibration and the peak temperature of the weld interface are increased significantly in RUSW.
2. A thin, uniform, and continuous IMC layer was observed at the faying surface when the DC reached 1100 A. The IMC layer increases rapidly with increasing the DC values. As the DC increased to 1500 A, evidence of a solidified microstructure was observed at the weld interface. Both the EDS and XRD results confirm that the IMC layer is mainly composed of CuAl₂.
3. The intermetallic reaction layer resulted in a good metallurgical bonding and increased the mechanical properties of the Al–Cu dissimilar joints. The lap shear load reached a maximum value of 550 N at the DC level of 1100 A, while for USW the maximum lap shear load was much lower (about 300 N).

Copper and aluminum, with their high electrical and thermal conductivity, are preferred in the electronics industries and battery electric vehicles. Hence, a significant amount of Al–Cu joining is needed to transmit electricity. Unfortunately, joining of Al–Cu by conventional fusion welding methods is difficult due to poor weldability, high levels of distortion and rapid formation of bulk intermetallic compound (IMC). Therefore, solid-state welding methods, such as ultrasonic welding (USW) has

received much attention as alternative joining techniques for Al–Cu.[33]

3.3 Solid-state ultrasonic spot welding of SiCp/2009Al composite sheets

It has been challenging to join aluminum matrix composites (AMCs) using conventional fusion welding processes due to the occurrence of segregation and deleterious reactions between the reinforcement particles and liquid aluminum in the fusion zone. Development of robust welding processes to join AMCs thus holds the key in advanced lightweighting structural applications in the transportation sectors. The purpose of the study was to explore the weldability of AMCs via a solid-state welding technique – ultrasonic spot welding (USW). In this study 1.5 mm thick 17 vol.% SiCp/2009Al composite sheets in the annealing (O) and T6 conditions were subjected to USW, respectively, with the aim to demonstrate the welding feasibility of the composites. Microstructure, X-ray diffraction, microhardness and lap shear tensile tests were performed to evaluate the weld zone (WZ) characteristics in the USW joints. A characteristic band consisting of finer and denser crushed SiC particles that were uniformly embedded in the aluminum matrix was observed to occur in the WZ. The WZ of both types of joints had a much higher hardness than that of their respective base metal. The lap shear tensile fracture load increased with increasing welding energy and satisfied the requirement of AWS standard D17.2 for spot welding. [34]

To conclude, USW of 1.5-mm thick SiCp/2009Al–O and SiCp/2009Al–T6 composites was successfully achieved. Both types of welded joints exhibited higher volume fractions of SiC particles in WZ, creating a distinctive band-like structure consisting of crushed fine SiC particles uniformly embedded in the aluminum matrix. This was mainly attributed to the squeeze-out effect of softer Al during USW due to the severe shear strain rate caused by the high frequency vibration energy. The generation of h phase during the aging process of parent metal was re-confirmed by XRD. The peaks of XRD showed that volume fraction of h phase before and after welding remains same. The WZ of the joints had a much higher hardness than that of their respective base metal due to the presence of finer and denser crushed SiC particles. The 2000 J welded samples experienced higher hardness than that of 1000 J welded samples. This occurred because at higher welding energy, high frequency (20 kHz) ultrasonic vibration applies to the samples for longer period of time leads higher temperature, thus more Al being squeezed off in 2000 J energy input sample. The lap shear tensile fracture load increased as the welding energy increased, and the maximum lap shear tensile load of the USWed 2009Al–O/SiC and 2009Al–T6/SiC composites was obtained to be 3.1 and 4.5 kN, respectively, which fulfilled the requirements of AWS D17.2 standard.

4. Conclusion

All the studies have shown that USW technique satisfies criteria for joining

dissimilar materials with different thicknesses and composition structures. Moreover, the process ultrasonic welding is environmentally friendly since no flux material is required in order to join materials. In addition, energy used in ultrasonic welding is under 2000 watts and it is completed in less than a half second, meaning that it uses very little energy. This process does not change the internal structure of materials. Moreover, the duration of ultrasonic welding technique finishes very rapid and in short time intervals. It provides reliability in combining welding parameters. Joints produced by ultrasonic welding are stable, strong and the composition of dissimilar materials is not damaged so the chemical structure stays constant throughout. Moreover, energy consumption is low thus energy is saved.

Ultrasonic welding is extensively used in fields of electronic, aerospace, automotive industry, medical industry since the chemical composition is not harmed nor changed and joints on microscale are able to be produced. For example, the most important thing in electronics industry is that the devices do not lose thermal and electrical conductivity. Thus, the USW technique enables the bonding of copper and aluminum and this technique does not damage these properties. Most commonly electronic parts welded by USW technique are capacitors, electric motors, transformers, microcircuits, transistors, diodes.

With the usage of ultrasonic welding slightly the weight of aerospace and

automotive devices can be reduced that leads to the fuel efficiency and less environment pollution. Most important fact is that the joints between dissimilar materials have high economic and industrial advantage. Aluminum is a material that is slightly hard to weld due to its high thermal conductivity, and that is the reason why ultrasonic welding technique produces solid state weld that is achievable. Since Aluminum is a light material and due to its softness it makes it suitable and commonly used material for aerospace engines.

5. References

- [1] Annoni M, Carboni M. Ultrasonic metal welding of AA6022/T4 lap joints: Part I- Technological characterization and mechanical behavior. *Sci Technol Weld joining* 2011; 16(2):107-15
- [2] Weare NE, Monroe RE. Ultrasonic welding of heat-resistant metals. *Weld Res Suppl* 1961:35s-7s
- [3] Bakavos D, Prangell PB. Mechanism of joint and microstructure formation in high power ultrasonic welding 6111 aluminum automotive sheet. *Mater Sci Eng A* 2010; 527: 6320-34
- [4] Patel VK, Bhole SD, Chen DL, Influence of ultrasonic welding on microstructure in a magnesium alloy. *Scr Mater* 2011; 659:11-914
- [5] Kim J. Weldability of $\text{Cu}_{54}\text{Zr}_{22}\text{Ti}_{18}\text{Ni}_6$ bulk metallic glass by ultrasonic welding processing. *Mater* 2014; 130: 160-163
- [6] Kim J. Weldability of $\text{Cu}_{54}\text{Zr}_{22}\text{Ti}_{18}\text{Ni}_6$ bulk metallic glass by ultrasonic welding processing. *Mater* 2014; 130: 160-163
- [7] Ahmad M, Akhter J. I, Babu S.S, Choudary M.A, Tariq N.H, Shakil M. Effect of ultrasonic welding parameters on microstructure and mechanical properties of dissimilar joints. *Mater* 2014; 55: 263-273

- [8] Ahmad M, Akhter J. I, Babu S.S, Choudary M.A, Tariq N.H, Shakil M. Effect of ultrasonic welding parameters on microstructure and mechanical properties of dissimilar joints. *Mater* 2014; 55: 263-273
- [9] Ahmad M, Akhter J. I, Babu S.S, Choudary M.A, Tariq N.H, Shakil M. Effect of ultrasonic welding parameters on microstructure and mechanical properties of dissimilar joints. *Mater* 2014; 55: 263-273
- [10] Ahmad M, Akhter J. I, Babu S.S, Choudary M.A, Tariq N.H, Shakil M. Effect of ultrasonic welding parameters on microstructure and mechanical properties of dissimilar joints. *Mater* 2014; 55: 263-273
- [11] Pollock TM. Weight loss with magnesium alloys. *Science* 2010;328:986–7.
- [12] Nie JF, Zhu YM, Liu JZ, Fang XY. Periodic segregation of solute atoms in fully coherent twin boundaries. *Science* 2013;340(6135):957–60.
- [13] McNutt M. Climate change impacts. *Science* 2013;341(6145):435.
- [14] Ash C, Culotta E, Fahrenkamp-Uppenbrink J, Malakoff D, Smith J, Sugden A, et al. Once and future climate change. *Science* 2013;341:472–3.
- [15] Murray J, King D. Climate policy: oil's tipping point has passed. *Nature* 2012;481(7382):433–5.
- [16] Shakun JD, Clark PU, He F, Marcott SA, Mix AC, Liu ZY, et al. Global warming preceded by increasing carbon dioxide concentrations during the last deglaciation. *Nature* 2012;484(7392):49–54.
- [17] Joost WJ. Reducing vehicle weight and improving U.S. energy efficiency using integrated computational materials engineering. *JOM* 2012;64:1032–8
- [18] Ghali E, Dietzel W, Kainer KU. General and localized corrosion of magnesium alloys: a critical review. *J Mater Eng Perf* 2013;22(10):2875–91.
- [19] Fang DQ, Ma N, Cai KL, Cai XC, Chai YS, Peng QM. Age hardening behaviors, mechanical and corrosion properties of deformed Mg–Mn–Sn sheets by prerolled treatment. *Mater Des* 2014;54:72–8
- [20] Gu YH, Cai XJ, Guo YJ, Ning CY. Effect of chloride ion level on the corrosion performance of MAO modified AZ31 alloy in NaCl solutions. *Mater Des* 2013;43:542–8.
- [21] Hütsch LL, Hütsch J, Herzberg K, dos Santos JF, Huber N. Increased room temperature formability of Mg AZ31 by high speed friction stir processing. *Mater Des* 2014;54:380–8.
- [22] Wu XX, Yang XY, Ma JJ, Huo QH, Wang J, Sun H. Enhanced stretch formability and mechanical properties of a magnesium alloy processed by cold forging and subsequent annealing. *Mater Des* 2013;43:206–12.
- [23] Zhang H, Huang GS, Roven HJ, Wang LF, Pan FS. Influence of different rolling routes on the microstructure evolution and properties of AZ31 magnesium alloy sheets. *Mater Des* 2013;50:667–73.
- [24] Macwan A, Jiang XQ, Li C, Chen DL. Effect of annealing on interface microstructures and tensile properties of rolled Al/Mg/Al tri-layer clad sheets. *Mater Sci Eng A* 2013;587:344–51.
- [25] Zhang XP, Castagne S, Yang TH, Gu CF, Wang JT. Entrance analysis of 7075 Al/ Mg–Gd–Y–Zr/7075 Al laminated composite prepared by hot rolling and its mechanical properties. *Mater Des* 2011;32:1152–8.
- [26] Kim IK, Hong SI. Effect of component layer thickness on the bending behaviors of roll-bonded tri-layered Mg/Al/STS clad composites. *Mater Des* 2013;49:935–44.
- [27] Zhang XP, Yang TH, Castagne S, Gu CF, Wang JT. Proposal of bond criterion for hot roll bonding and its application. *Mater Des* 2011;32(4):2239–45.
- [28] Lee KS, Yoon DH, Kim HK, Kwon YN, Lee YS. Effect of annealing on the interface microstructure and mechanical properties of a STS–Al–Mg 3-ply clad sheet. *Mater Sci Eng A* 2012;556:319–30.
- [29] Lee KS, Kim JS, Jo YM, Lee SE, Heo J, Chang YW, et al. Interface-correlated deformation behavior of a stainless steel–

Al-Mg 3-ply composite. *Mater Charact* 2013;75:138–49.

[30] Chang H, Zheng MY, Gan WM, Xu C, Brokmeier HG. Texture evolution of the Mg/Al laminated composite by accumulative roll bonding at ambient temperature. *Rare Metal Mater Eng* 2013;42(3):441–6.

[31] Luo CZ, Liang W, Chen ZQ, Zhang JJ, Chi CZ, Yang FQ. Effect of high temperature annealing and subsequent hot rolling on microstructural evolution at the bond-interface of Al/Mg/Al alloy laminated composites. *Mater Charact* 2013;84:34–40.

[32] Matsumoto H, Watanabe S, Hanada S. Fabrication of pure Al/Mg–Li alloy clad plate and its mechanical properties. *J Mater Process Technol* 2005;169:9–15

[33] Yingwei Yang, Biao Cao. Investigation of resistance heat assisted ultrasonic welding of 6061 Aluminum alloys to pure copper. *Materials and Design* 74 (2015) 19–24

[34] Patel V.K, Bhole S.D, Chen D.L, Ni D.R, Xiao B.L, Ma Z.Y, Solid-state ultrasonic spot welding of SiCp/2009Al composite sheets. *Materials and Design* 65 (2015) 489–495