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Effects of tool rotation speed and pin geometry on properties in friction stir welding of brass

Takım dönme hızı ve karıştırıcı uç geometrisinin pirincin sürtünme karıştırma kaynağında özelliklere olan etkileri

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Effects of Tool Rotation Speed and Pin Geometry on Properties in Friction Stir Welding of Brass

Highlights

- *CuZn37 sheets were joined by different stirrer pins and tool rotation speeds by friction stir welding.*
- *A defect-free weld having weld performance of 81% of the base metal was achieved.*
- *Heat-affected zone having coarse grains, and stir zone having fine grains were detected in the weld zone.*
- *The stir zone slightly softened according to the base metal.*
- *The peak temperature in the stir zones was increased with increasing of tool rotation speed.*

Graphical Abstract

Effects of tool rotation speed and pin geometry were investigated by tensile and microhardness tests, and optical and scanning electron microscopies. The rising of temperature in stir zone was measured by K-type thermocouple.

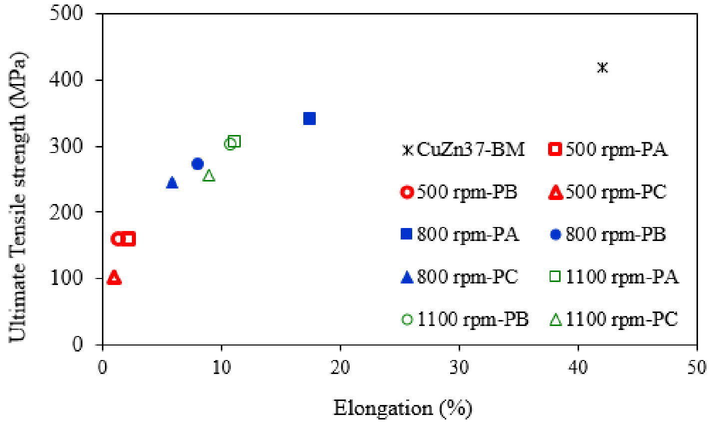

Figure. UTS and PE of the welded samples according to the used joint conditions

Aim

There is a lack of experimental work on the effects of tool rotation speed with stirrer pin geometry in friction stir welding of brass materials on the weld properties. Thus, it has been aimed to achieve the optimum rotation speed and pin profile of the tool.

Design & Methodology

Friction stir welding was used various tool rotation speeds and stirrer pin types.

Originality

Peak temperature was measured in the weld center.

Findings

An insufficient material mixing and weld defects were formed by using a lower tool rotation speed caused, regardless of the pin profile. The best results obtained by a pin having right hand threaded conical profile.

Conclusion

The best tensile properties were obtained by a pin having right hand threaded conical profile at 800 rpm.

Declaration of Ethical Standards

The author of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Effects of Tool Rotation Speed and Pin Geometry on Properties in Friction Stir Welding of Brass

Araştırma Makalesi / Research Article

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ABSTRACT

In this study, CuZn37 brass sheets were joined by applying three different stirrer pins and different tool rotation speeds of 500, 800, and 1100 rpm by friction stir welding, while tool travel speed (40 mm·min^{-1}), and other parameters were kept constant. Effects of the used weld parameters were investigated in weld zone and mechanical features via tensile test, microhardness measurement and optical and scanning electron microscopies. The rising of temperature in stir zone was also measured by using K-type thermocouple. The tensile test results show that a defect-free joint having weld performance of 81% of the base brass metal was achieved by using a conical pin without flattened at tool rotation speed of 800 rpm. The stir zone of this joint slightly softened according to the base metal and the heat-affected zones showed the lowest hardness values. The peak temperature in the stir zones was increased with increasing of tool rotation speed, consequently arrived to 804 °C at 1100 rpm.

Keywords: FSW, CuZn37, tool rotation speed, pin geometry, weld performance.

Takım Dönme Hızı ve Karıştırıcı Uç Geometrisinin Pirincin Sürtünme Karıştırma Kaynağında Özelliklere olan Etkileri

ÖZ

Bu çalışmada, CuZn37 pirinç levhalar, takım ilerleme hızı 40 mm/dakika olarak sabit iken 500, 800 ve 1100 devir/dakika takım dönme hızlarında, üç farklı karıştırıcı uç ile diğer parametreler sabitken sürtünme karıştırma kaynağı ile birleştirilmiştir. Uygulanan kaynak parametrelerinin kaynak bölgesine ve mekanik özelliklere olan etkileri çekme testi, mikrosertlik ölçümleri, optik ve taramalı elektron mikroskobu yardımıyla araştırılmıştır. Ayrıca karışım bölgesindeki sıcaklık değişimi K-tipi termokupl kullanarak ölçülmüştür. Çekme testi sonuçları, 800 devir/dakika takım dönme hızında ve sadece konik bir kesite sahip uç ile ana metale göre %81 kaynak performansında, hatasız bir birleştirme yapılabildiğini göstermiştir. Bu birleştirmenin karışım bölgesi ana metale göre bir miktar yumuşamış olup, en düşük sertlikler ısı tesiri altındaki bölgelerde ölçülmüştür. Karışım bölgesinin maksimum sıcaklığı, takım dönme hızının artmasıyla yükselmiş, 1100 devir/dakika'da ise 804 °C'ye ulaşmıştır.

Anahtar kelimeler: SKK, CuZn37, takım dönme hızı, karıştırıcı uç geometrisi, kaynak performansı.

1. INTRODUCTION

Copper (Cu) and brass (CuZn) are among the most important engineering materials due to its good mechanical properties with corrosion resistance, outstanding thermal and electrical conductivities, etc. However, some difficulties such as necessity of higher heat input and/or using low weld speeds which are led to remarkable grain coarsening in widened heat affected zone (HAZ) accompanied by high distortion and residual stress come out according to joining of steels in conventional fusion weld techniques [1, 2]. Low strength in fusion zone due to zinc evaporation at ∼ 907 °C and oxidation, irregularities on weld surface, poor penetration depth are among the common problems for brass joints. Furthermore, the necessity of protection of welder's health from hazardous fumes, gases and ultraviolet radiation is another saving issue during fusion weld processes. Therefore, friction stir welding (FSW) can be alternatively applied to joining of brass to overcome such problems associated with cycling of melting and solidification during fusion welds [3-5]. FSW is one of the solid-state joint methods and has unique advantages include requirement of minimum work-piece preparations, no requirement of additional metal and shielding gas, easy of handling, high levels of repeatability of weld parameters, no or low distortion, relatively low heat input and high weld performance [6-8].

FSW has mainly used to welding of aluminum (Al) [9-11] in addition to magnesium (Mg) [12, 13], titanium [14], steel [15], composite [16], polymer [17], and Cu [2, 3, 18-25] since invented in 1991 by The Welding Institute. Recently, FSW has been also successfully carried out for bimetal applications such as Al/stainless steel [26], Al/Mg [27], Al/Cu [28] and Cu/CuZn [29, 30]

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under different FSW parameters. These studies show that FSW parameters in the trials have to be properly chosen in order to a sound and defect-free weld achievement. It can be said that rotation speed, travel speed, geometry, tilt angle and vertical pressure of used tool are among the main parameters having key role to obtain a sufficient weld properties [31, 32]. It can be understood that the most common two parameters from the literature are tool rotation speed (TRS) and tool travel speed, namely welding speed (WS). It can be said that this situation is currently existing for FSW of copper material [2, 18-23]. For all that the pin shapes determines the plasticized material transporting, macro and microstructural formation, too and thus joint quality is affected by its properties [24, 33-36]. Kumar and Suvarna Raju [24] carried out on FSW of copper by different stirrer pin profiles such as taper cylindrical, taper cylindrical with threaded, triangular, square, pentagonal, and hexagonal on properties of joints. They found that defect-free welds could be done by all pin profiles and also a joint having high level of weld performance was acquired by using square pin because it provides more number of pulsating actions and sweep large amount of material from plasticized zone during weld process. Similarly, Cartigueyen and Mahadevan [25] studied effects of different pin profiles (plain cylindrical, threaded cylindrical, triflute, triangle, square and hexagonal) on pure copper at constant TRS and WS to provide low heat input. According to researchers, more flowing material and frictional heat was generated with increasing contact area of pin and also tensile properties of joint were positively influenced by them. Ozer et al. [8] examined effects of TRS and WS on the microstructural properties, hardness, and fatigue strength of friction stir welded CuZn37 joints. They concluded that using a higher TRS at constant WS value resulted in high heat, and severe deformations, these led to growing grains in stir zone (SZ), thermo-mechanical affected zone (TMAZ), wide welding zone, low hardness, low fatigue life and formation of tunnel defect. Emami and Saeid [37] applied various TRS and WS to single-phase brass sheets and observed that sound welds can be obtained by using optimum parameters. According to them, the grain sizes in SZ decreased with increasing WS and/or decreasing TRS. Moreover, the changing in grain size affects the hardness of SZ decreased by increasing TRS and increased by increasing WS. However, an info about weld performance has not be presented in that article. Xie et al. [38] investigated effects of various rotational speeds on microstructural evolution and mechanical properties of CuZn38 brass joint using FSW. According to them, TRS is one of the significant parameters and increasing TRS decreased the average grain size in SZ and in yield strength, but led to ductility of the welds. Cam et al. [39] employed FSW technique to welding of CuZn37 brass alloy using various TRS and WS. Author reported that the tensile strength increased by increasing TRS together with WS. Moghaddam et al. [40] attempt the welding of CuZn30 brass plates by FSW at different WS and a constant TRS. They saw that increasing WS led to an increase in yield strength, but it has harmfully effect on percent elongation. In another a study by Meran [41] has been pointed out that to apply both lower and higher WS led to microstructural defects and lack of penetration and tensile strength also increased with increasing WS. Park et al. [42] investigated FSW of CuZn40 brass using different TRS and WS. Authors reported that lack of penetration occurred at low TRS and high WS conditions. According to authors, increment in WS resulted in increasing of yield and tensile strength and decreasing of percent elongation. Emamikhah et al. [43] investigated the effects depending on heat input amount of pin profiles using chamfered taper, single-threaded taper, three-flute, threaded cylinder, threaded taper, spline, and hexahedron at a constant TRS for FSW of CuZn40 alloy. The results show that higher heat input required in order to sufficiently material mixing and improved mechanical features. Higher heat produced on AS with threaded cylindrical pin, as threaded taper was resulting in higher heat and hardness on RS. In addition, lower temperature was observed using hexahedron pin type. On the other hand, there is a limited amount of survey related to the effects of TRS with stirrer pin geometry for brass material. Gecmen et al. [44] tried to FSW of CuZn37 brass used different pins which was straight cylindrical, tapered cylindrical (conical), threaded conical, and square and various TRS of 1040, 1500, 2080 rpm and WS of 30-113 mm·min^{-1}. According to the researchers, the highest weld performance was achieved by the pin with threaded conical and also they suggested that the tensile strengths of the joints were generally influenced by the grain size depending on different TRS and WS. The grain size decreased with the increasing TRS and WS and this caused the obtaining of higher tensile strength. As can be seen in the presented literature survey above there is a lack of work on the effects of TRS with pin geometry of brass materials on the joint features and therefore, the author aimed to achieve the optimum tool rotation speed and tool pin profile in the present work and it has been studied to this aim.

2. MATERIAL AND METHOD

Commercial cold-rolled CuZn37 (37.03 Zn and 62.84 Cu) brass material with dimensions of 200 (length) × 90 (width) × 3 (thickness) was used to FSW in butt joint process in this study (chemical composition in wt. % and dimensions in mm). All welds were done parallel to rolling direction using the tools made by EN X40CrMoV5 material due to its high strength at elevated temperature. The tools consist of a shoulder diameter of 15 mm with concave shaped. Three different pin profiles have right hand threaded which are only conical (profile A, PA), conical with single flat (profile B, PB), conical with double flats (profile C, PC) were utilized for FSW (Figure 1). The effects of TRSs of 500-1100 rpm with various stirrer pin geometries have been evaluated in FSW experiments. The other friction stir process parameters were kept constant, as can be seen in Table 1. The axes of all tools were adjusted to along the abutted surface of work-pieces, namely the tools were not offsetted before the weld and then the tool turning clockwise was held for 10 s after it penetrated of 2.9 mm into the work-pieces to provide preheating.

The temperature values in the stir zone were measured by a K-type thermocouple having a diameter of 1 mm. This type thermocouple is made up of bimetal Chromel (~ 90% nickel and 10% chromium) - Alumel (~ 95% nickel, 2% aluminum, 2% manganese and 1% silicon) conductors forming an electrical junction. It is described that the joined ends of these metal as a hot junction, the open end of each wire is a cold junction. When heated the hot junction, thermal energy is converted to electrical energy at the cold junction due to the temperature difference between two junctions in the thermocouple, namely produce a voltage in microvolt range. This voltage can be used to measure temperature by a device. Thus, Voltcraft Thermodatalogger 309 model a device was used to measure and collect the temperature values (Figure 2a), in this study. This device possess a measurement range from -200 °C to +1370 °C and measuring accuracy of ± (0.3%+1 °C). The temperature values were recorded at interval time of 1 second during the FSW processes, so number of approximately 310, 330 and 350 measurements were gained for the experiments at 500, 800 and 1100 rpm, respectively. Then, the collected data were plotted as graphs by Microsoft Excel. The measurement by the thermocouple was done in a predrilled hole at mid-thickness of the abutted surface for butt joint under conditions of 500, 800, and 1100 rpm by the tool with PA. The hole length was 25 mm and the closed end of the hole was 15 mm behind the keyhole center, as shown in Figure 2b. The reason of the measurement on this point is observe that reachable to peak point in to be welded brasses due to continuously tempered around keyhole through all process. The stirrer pin profile effect on the heat input level was ignored, since it was considered that TRS has more significant effect on heat generation than pin geometry.

Tensile tests including three specimens were performed by a Zwick / Roel Z050 tester at a cross-head speed of 2.5 mm·min^{-1}, according to ISO 4136:2012 and average values of ultimate tensile strength (UTS) and percent elongation (PE) presented in results to reveal the weld properties according to brass base metal. The joint performance and ductility performance were calculated by using formulas UTS_{weld} / $UTS_{base\ metal}$ × 100 and PE_{weld} / $PE_{base\ metal}$ × 100, respectively. Tensile samples were cut by waterjet according to EN 895 (Figure 3). In order to observe microstructural changes and measure microhardness in joint zone, polished cross-sectional samples were etched by a solution consisted of 100 ml of H_2O, 4 ml of saturated NaCl, 2 g of Cr_2K_2O7, and 5 ml of H_2SO_4. Optical microscope (OM) inspection in weld zones was made by a Nikon Eclipse L150A equipped with Clemex Vision Lite image analysis software and a Jeol JSM 6060LV scanning electron microscope (SEM) equipped with energy dispersive X-ray spectroscopy (EDS) apparatus was used to characterize fracture surface of the failed tensile test specimens. Vickers microhardness (HV) test was utilized on etched cross-sectional sample applying a load of 100 g and a dwell time of 10 s using a 402 MVD / Wilson hardness tester. OM and SEM observations and microhardness test were made on the joints having the highest tensile performance.

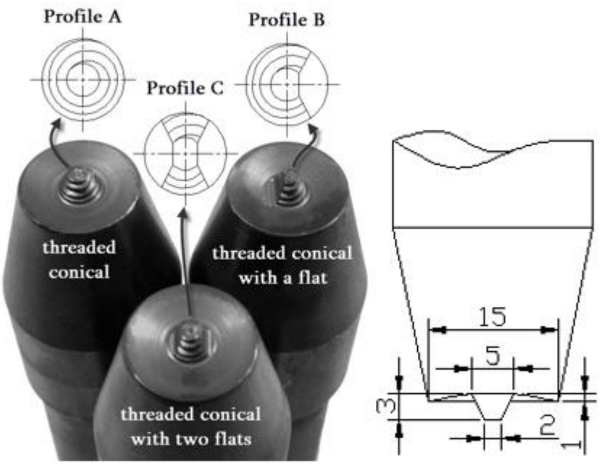


Figure 1. Images and geometrical details of the tools used in FSW (dimensions in mm)

Table 1. FSW parameters used in the process

Stirrer Pin Type	TRS (rpm)	tool travel speed (mm·min^{-1})	tool tilt angle (°)	tool dwell time in starting (s)	tool plunge depth (mm)	tool offset (mm)
Profile A (PA)	500 800 1100	40	2	10	2.9	0
Profile B (PB)	500 800 1100					
Profile C (PC)	500 800 1100					

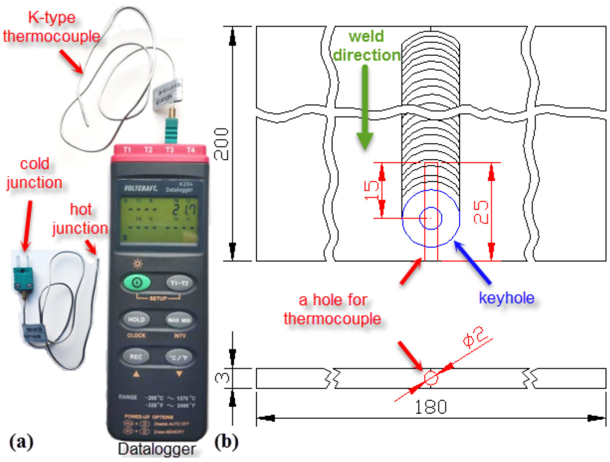


Figure 2. (a) Datalogger with a K-type thermocouple image and (b) schematic drawing of FSW configuration (dimensions in mm)

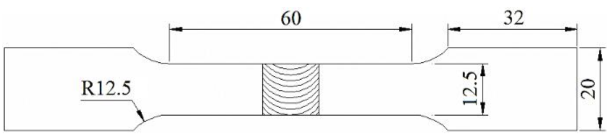


Figure 3. Geometrical details of tensile test sample for butt joint by FSW (dimensions in mm)

3. RESULTS AND DISCUSSION

Figure 4 shows the acquired temperature measurements in the SZ via the thermocouples in FSW using a PA type stirrer pin. The peak temperature increased with increasing TRS due to the frictional heat input in accordance with previous studies [8, 20, 23, 39, 42, 45], and it reached to 804 °C for TRS of 1100 rpm. On the other hand, there is no significant change in the increment of the peak temperature with increasing of TRS from 800 to 1100 rpm, as can be seen from the graphs in Figure 4. It is obvious that the peak temperature generated at the weld center (tool center), since the heat source is tool in this technique [45]. Thus, it is believed that a probable maximum temperature was measured on the experiments in this FSW conditions. After the tool passed the thermocouple tip, the peak temperature rapidly decreased in a few seconds and then cooling rate slowed down remarkably. The welds at 800 and 1100 rpm slowly cooled due to the higher heat input according to 500 rpm. All peak values are lower than the melting point (900-920 °C) and zinc evaporation temperature (907 °C) of brass materials. Therefore, it can be said that the used parameters are suitable to goal of the application a solid state welding.

FSW studies show that TRS value with the stirrer pin profile played a remarkable role on to make a sound joint. It can be firstly said that volumetric tunnel-like cavities and lack of penetration along the roots formed at the lowest TRS that 500 rpm regardless of the used pin profile due to improper stirring of the material around the pin, as can be seen in cross-sections in Figure 5a. This cause-effect relationship is accordance with the earlier work [23]. As stated in the report [34], a higher TRS is required to make a good and sound weld. The defects mainly occurred on the area close to the pin surface at the advancing side (AS) rather than the retreating side (RS). Also, the mentioned defects formation is obviously observed for the stirrer pin consist PC. Nevertheless, these defects disappeared with increasing TRS, but the surface defect formed at this condition (Figures 5b and c). Although the higher TRS used to provide the efficient plasticity and mixing of material, PC and PB types led to rising the defect amount in the experiments. It is believed that PB and PC include the sharp edges behaved like a drill bit, while the rotating of tool in the higher rotation speed, so the material reduced at the close to top surface of joints. This unfavorable situation is clearer for PC due to occurrence more sharp edges than the other. Additionally, the reduction of cross-section distances underneath outer periphery shoulder stand out at RS compared to AS according to Figures 5b and c. It is seen that a little thinning relatively occurred on the cross-section for the joint at 800 rpm by using PA. Finally, to use lower TRS independently from the pin geometry resulted in a narrower weld zone for all trials.

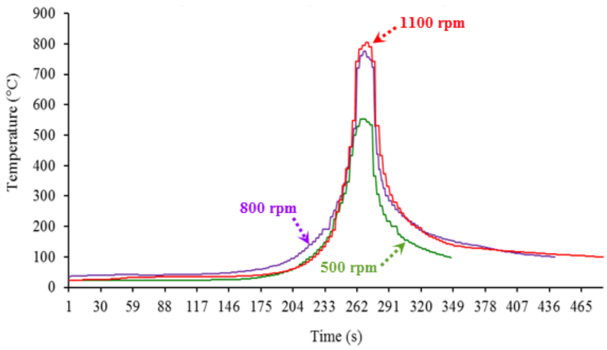


Figure 4. Temperature distributions dependence on TRS values during FSW

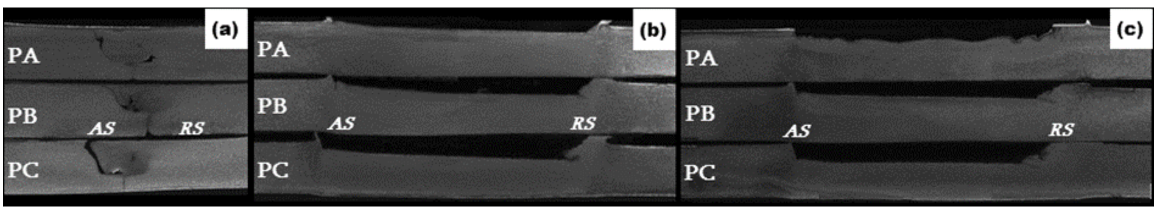


Figure 5. Macro images of FSW samples at (a) 500 rpm, (b) 800 rpm and (c) 1100 rpm depending on the pin profiles

UTS values with PE and failed sample image are given in Figures 6 and 7, respectively. The highest TS value of 339 MPa with PE of 17.5 were achieved in all efforts by threaded conical pin tool (PA) at TRS of 800 rpm in accordance with the macroscopic observations. This weld showed the joint performance of 81% and ductility performance of 41.6% according to CuZn37 brass base metal (UTS = 418 MPa, PE = 42%). A weld at 1100 rpm using PA which akin to macrostructurally the best weld displayed close to TS, too. Therefore, first of all the most suitable pin type for the experiments is PA. In addition, PB generally displayed close to properties of PA despite of its asymmetrical geometry. In some experiments about pure copper, Cartigueyen and Mahadevan [25] found that threaded cylindrical pin profile is more effective to provide higher tensile strength due to sufficient heat generation and material transporting, as best joint could be fabricated by square pin because of the same reasons according to Kumar and Raju [24]. In conclusion, a favorable weld having less weld defect in comparison with the others in addition to a better mixing and transporting of plasticized material was obtained with the threaded conical pin tool in the present work. This revealed that the measured temperature is suitable to the aim above. It is suggested that the crack initialed in earlier mentioned that decreasing cross-sectional area at RS and then propagated during the test (Figure 7). It is understood from the observations that the macro defects such as thinning in section and possible notch effect on RS main factors are with microstructural properties for the determining of tensile properties. SEM images denoting the presence of shallow-hole type dimples (Figure 8) on the fractured surface for 800 rpm using PA indicates that a typical ductile fracture mode occurred, despite of larger voids comparing to the base metal. The difference of dimple sizes between the BM and the best joint has explained why TS and percent elongation of the joint was low than that of the BM. In addition, it was come out that there are no remarkably altering in the compositions of the weld zone for the best joint performance with regard to EDS analysis results (Figure 8).

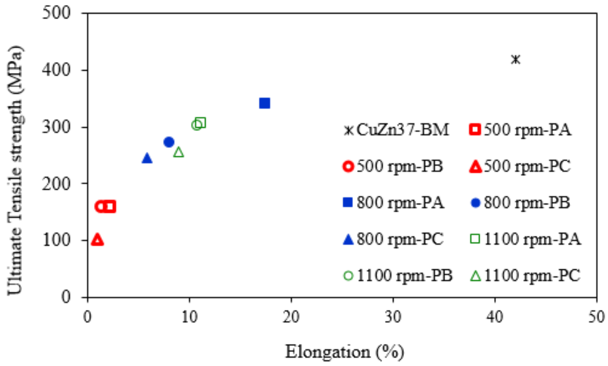


Figure 6. UTS and PE of the welded samples according to the used joint conditions

As presented in Figure 9, the typical zones which are stir zone and the heat-affected zone (HAZ) as well as the base metal (BM) have been occurred in friction stir process of the CuZn37 brass. The grains in the BM contain more and large deformation twins. HAZ consisted of coarse grains with relatively less twins in comparison to that of the BM. Gecmen et al [44] suggested that the grain growth in HAZ directly affected the tensile strength. As can be seen in Figure 7, in the specimen failure took place on the HAZ, as pointed out by Gecmen et al. [44]. However, a thermo-mechanically affected zone was not stated after FSW process (Figure 9d) in contrast to some studies observation about brass joints [8, 44]. On the other hand, Cam et al. [39] was not declared occurrence of TMAZ in the observations about FSW of CuZn37. There is a difference of opinion between this study and previous studies [8, 44] on the determine TMAZ because, as well known, TMAZ is characterized by elongated and/or rotated grains between HAZ and SZ due to the forging action of tool [31, 34]. It is thought that TMAZ has not clear both in this study and previous studies. The recrystallization temperature for CuZn37 brass is changed from 450 to 600 °C. It was recorded approximately 777 °C in the SZ, therefore it can be easily that recrystallized fine equiaxed brass grains formed in the SZ caused by combination of intense plastic deformation and raised temperature [23].

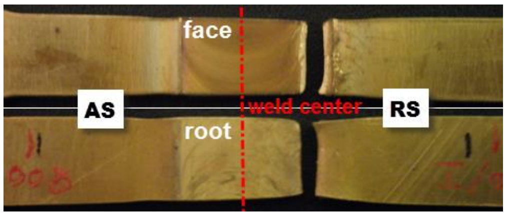
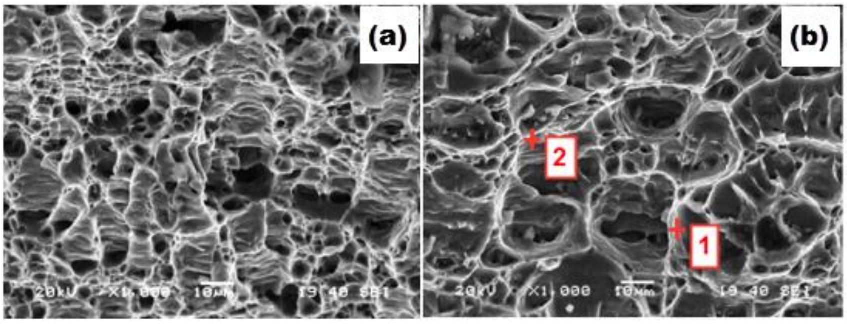


Figure 7. Face and root side images of failed FSW sample having the highest performance at 800 rpm by using PA after tensile test

The mentioned above microstructural features reflected to the microhardness measurement results, as can be seen in Figure 10. The BM and SZ have mean hardness of 135.2 HV (std. dev. 2.3) and 117.9 HV (std. dev. 1.7), respectively. Namely, the SZ softened according to the BM despite of refining in grains. Similar result was reported on some studies about brass [8, 39], while the knowledge about hardness was not presented by Gecmen et al. [44]. It is suggested that there are two dominant factors which grain refinement and annealing effect on hardness in SZ. If SZ is exposured to low heat input depending on used parameters, hardness increases in SZ because of the grain refinement. On the contrary, hardness decreases with effect of annealing independent with Hall-Petch relation [18, 19, 23, 24]. It is remembered that the deformation twins has additionally influence on the hardness increment in the BM. Consequently, it can be said that the SZ of the joint at 800 rpm was influenced by the annealing softening effect during dynamic recovery and recrystallization. The HAZ at both side of weld zone showed the lower values (~ 88 HV) due to the coarse grains. In addition, a symmetrical



	Elt.	Line	Intensity (c/s)	Error 2-sig	Conc	Units
1	Cu	Ka	220.94	9.400	62.946	wt.%
	Zn	Ka	101.12	6.360	37.054	wt.%
2	Cu	Ka	109.52	6.617	63.110	wt.%
	Zn	Ka	31.39	3.543	36.890	wt.%

kV 20.0
Takeoff Angle 35.0°
Elapsed Livetime 10.0

Figure 8. SEM images on the fractured surface from (a) CuZn37 base metal and (b) the best joints with EDS analysis results

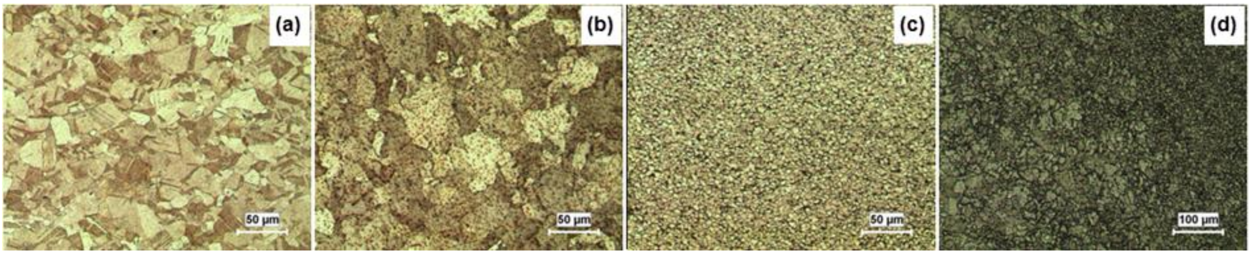


Figure 9. Microstructures in the weld zone of the FSWed joint at 800 rpm by using PA (a) BM, (b) HAZ, (c) SZ, and (d) transition between HAZ and SZ

hardness distribution occurred in the weld zone and the hardness gradually decreased from the BM to the HAZ. It can be expected that the fracture had happened within the HAZ in accordance with the presented macro and microscopic observations.

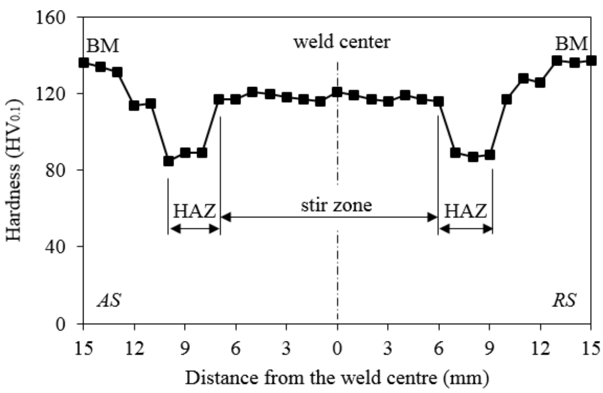


Figure 10. Microhardness distribution in weld zone of the joint at 800 rpm by using PA

4. CONCLUSION

In this study, the author evaluated the effects of different TRS by using various pin geometries on the CuZn37 brass in the FSW. The weld trials were influenced by these parameters. The lowest TRS of 500 rpm independent of pin profile caused tunnel-like defect and cavities in all welds. Using a higher TRS led to a higher peak temperature, it reached to about 804 °C at 1100 rpm. But the difference between 800 and 1100 rpm is close which 27 °C, as for 500 and 800 rpm, it is 250 °C. The best tensile properties were obtained at TRS of 800 rpm when a pin having right hand threaded conical profile was used. The tensile strength and elongation of the best joint are 339 MPa and 17.5%, respectively. SEM image revealed the ductile fracture for the joint. The unaffected base metal, heat-affected zone having coarse grains, and recrystallized stir zone having fine grains were detected by microstructural observations. A softened stir zone was detected with respect to the base metal due to the annealing effect. The average hardness value of the stir zone is approximately 118 HV. The lowest hardness values were detected in the heat-affected zones.

DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

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