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Research Article

Joining of Commercial Pure Copper via Self-reacting Friction Stir Welding

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ABSTRACT

Three mm thick plates of commercial pure copper were welded via friction stir welding method using a floating bobbin tool. The effect of different process variables such as the tool transverse speed and the tool rotation speed were examined in order to create a weld with the desired properties. A defect-free weld was obtained at a rotation speed of 1400 rpm and a transverse speed of 18 mm/min with a shoulder pinching gap of 2.7 mm. After the welding process, the soundness of the welds was confirmed by non-destructive methods of visual inspection and X-ray radiography. The results of the transverse tensile test showed that the as-weld joint efficiency was 86.4%, which was higher than the joint efficiency made by the fusion welding method. The strength of the welds was such that the fracture of the workpiece was in the heat affected zone after the tensile test. On the other hand, the grain size of the weld was significantly less than the base metal. The lowest hardness around 40VHN was attributed to the middle of the thickness of the weld, while the highest hardness was in the vicinity of the lower shoulder of the tool, which was about 80 VHN.

1. Introduction

Although copper has many good properties such as high electrical and thermal conductivity, excellent corrosion resistance and good ductility, but due to its low weldability, its applications are limited. On the other hand, due to the higher thermal conductivity and thermal expansion coefficient, the distortion caused by copper welding is higher than that of steel. Furthermore, during copper arc welding, oxygen in the grain boundaries segregates, it leads the weld joint to become brittle. However, because of the high thermal conductivity of copper, the necessary thermal concentration for base metal melting is not provided during the welding process which is why the lack of fusion defect occurs. Since in the friction stir welding (FSW) method, heat is generated at one point as a result of the friction between the tool and the base metal, this method is suitable for copper welding [1-4].

Friction stir welding is an innovative welding method in which the welding of the workpieces occurs in the solid state. Weld properties are usually similar to the base metal. Welds created by this method have higher strength, higher fatigue life, lower residual stress and higher corrosion resistance compared to the welds created by fusion welding methods. This method is widely used in industry to join aluminum alloys in space-crafts, airplanes, trains, ships, cars, etc. Recently, industrial applications for the friction stir welding of copper have been developed. Regarding industry applications, the friction stir welding of copper is utilized in the manufacturing of heat exchangers, coolers, backing plates for coating equipment, and reservoirs for nuclear waste. Hitachi Cable Company and Messi Hitachi Products Co. in Tsuchiura, Japan, use the friction stir welding method in mass production of water cooled copper backing plates. These plates are

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used as target holder plates in sputtering equipment. In Sweden, thick copper tanks are used to manage waste and eliminate nuclear waste. The waste must be buried deep in the ground. Accordingly, the waste must be put in containers that have both mechanical strength and high corrosion resistance so that they are not destroyed by environmental factors. Hence, the waste is first put in the cast-iron containers and then the container is placed inside a copper tank. Due to the importance of the issue, to the manner in which the doors of these tanks are sealed and closed is considered very important. In the past, the only applicable method for welding these thick copper tanks was electron beam welding. Since 1997, the friction stir welding method has replaced electron beam welding as a high-efficiency method [5-9].

Self-Reacting Friction Stir Welding (SRFSW) is a new technique of the Conventional Friction Stir Welding (CFSW). In this technique, the pin at the end of the welding tool is extended behind the workpiece and ends at the other shoulder, in such a way that the second shoulder is in contact with the back of the workpiece (Fig. 1). In other words, in the friction stir welding method, the tool consists of two shoulders, the upper shoulder is in contact with the face of the workpiece and the lower shoulder is in contact with the back of the workpiece, and the pin is located between these two shoulders. Thus, unlike CFSW, there is no need for a backing plate because the second shoulder has the same function. This kind of tool is also called a bobbin tool. In tool design, the distance between the shoulders can be considered constant or variant. The first advantage of this technique is that the huge amount of vertical force in the CFSW is balanced due to the symmetrical nature of the tool. Accordingly, the size and complexity of the necessary set of tools (welding machine, backing plate, clamps, etc.) for welding large structures is reduced [10, 11].

The symmetry of the tool also makes the applied stir and the incoming heat to the workpiece symmetrical; therefore, preventing problems such as minor penetration and, consequently, welding root defects. In this regard, tool design is of particular importance in the success of the process. Changing the tool design from CFSW to SRFSW by adding the lower shoulder caused many differences in the process, some of which are listed in Table 1 [12-15].

The quality of the joints and alloys via friction stir welding method was evaluated by the researchers, the summary of the field of commercial pure copper joining is presented in Table 2.

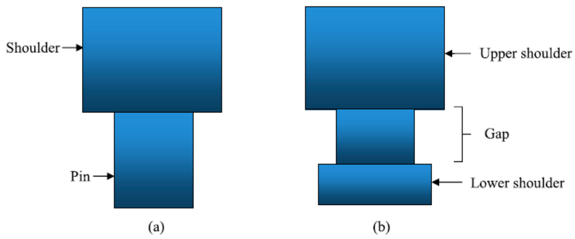

Fig. 1. Schematic image of the tool in a) CFSW; and b) SRFSW [10].

Table 1. Comparison of the CFSW and SRFSW [12]

Conventional friction stir welding	Self-reacting friction stir welding
The tool is made of one shoulder.	The tool has two shoulders.
Backing plate is required in order to withstand the vertical force applied by the tool.	The second shoulder acts as a backing and the tool does not require a backing plate.
One-shoulder layout of the tool produces less heat during the process.	The dual-shoulder layout of the tool provides sufficient heat on both sides of the work-piece.
Most of the heat generated during the process is transmitted through the backing plate.	All heat generated during the process is consumed for heating the work-piece and is not wasted.
The cross-sectional region of the weld zone is cup-shaped and the grain size distribution in this region is not uniform due to the cooling effect of the backing plate.	The cross-sectional region of the weld zone is in the form of a sand-clock and no appreciable change in grain size is observed along the work-piece’s thickness.
A lot of vertical force is applied to the workpiece by the tool during the process.	The vertical force applied to the work-piece during the process is almost zero and negligible.
Lack of complete penetration is one of the major defects of this method.	Full penetration joint is one of the features of this method.
For welding the thick sections, multi-pass welding should be performed.	This method is very effective in welding thick sections and it welds them in a single pass.

Table 2. Summary of research on the commercial pure copper joining via friction stir welding method

Material	Welding method	Description	Year	Reference
Cp-Copper	EBW FSW	Evaluation of welding properties based on welding method	2004	[16]
Cp-Copper	FSW	Creation of a fine-grained structure in the stirred zone	2007	[17,18]
Pure Copper	FSW	Evaluation of the effect of tool rotation speed on microstructure and mechanical properties of weld	2009	[19]
Pure Copper	FSW	Evaluation of welding speed on microstructure and mechanical properties of weld	2010	[20, 3]
Cp-Copper	FSW	Evaluation of the effect of cooling environment on the strength of the joint	2011	[21]
Cp-Copper	FSW	Evaluation of the effect of adding SiC particles on the microstructure and mechanical properties of weld	2011	[22]
Cp-Copper	FSW	Investigation of the effect of welding parameters on hardness strain behavior of the joint area	2012	[23]
Cp-Copper	FSW	Investigation of the effect of pin profile on microstructure and mechanical properties of weld	2012 2013	[24, 25, 26]
Pure Copper (C11000)	FSW TIG	Comparison of the effect of welding method type on mechanical properties of connection	2013	[27]
Copper	FSW	Evaluation of the effect of shoulder plunge depth on morphology and weld microstructure	2016	[28]
Cp-Copper	FSW	Improvement of strength and ductility by increasing vertical force during welding process	2017	[29]
Cp-Copper	FSW	Experimental evaluation of strain and strain rate during rapid cooling of copper during welding	2018	[30]
Copper	FSW	Numerical modeling and validation of copper friction stir welding	2019	[31]
Pure Copper	FSW	Use of fuzzy logic to determine the effect of welding parameters on tensile strength and elongation	2020	[32]

The novelty of this research lies in the assessment of copper weldability and the properties of friction stir welded samples using floating bobbin tools. Due to the high commercial and economic importance of copper in industry, in this study, an attempt was made to evaluate the possibility of copper double-sided welding using SRFSW technique. After welding process, in order to evaluate the quality of the welds, destructive and non-destructive testing methods like visual inspection, X-ray radiography, tensile test, hardness, and microstructural evaluation were applied.

2. Materials and Methods

In this study, 3 mm thick rolled plates made with commercial pure copper were used as base metal. The chemical composition of this alloy is presented in Table 3. These plates were welded via self-reacting friction stir welding method.

The base metal with the dimensions of 100 mm × 200 mm was selected to achieve dimensions of 200 mm × 200 mm after butt welding. SRFSW tool was designed and manufactured with two shoulders and a pin. It is worth mentioning that the tool is designed in such a way that by moving freely and normally to the surface, it will find a place of least resistance during welding through balancing the forces applied to each shoulder. Hence, this tool is called the floating bobbin tool. The schematic image of this tool with the fixture designed for it is shown in Fig. 3. The tool is made of hot working steel H13 (1.2344), which has reached 52 RC after heat treatment. MO40 (1.7225) micro-alloyed steel was used to fabricate a rigid fixture that could keep the plates fixed during the welding process. Pin, upper shoulder and lower shoulder diameter were selected 6, 22 and 22 mm, respectively.

Table 3. Chemical composition of commercial pure copper used in this study

alloy	alloying elements (wt.%)								
	Cu	Zn	Pb	Sn	P	Mn	Fe	Ni	Si
Cp-Cu	99.9	<0.005	0.017	<0.005	0.011	0.013	0.017	<0.005	0.005

Threaded cylindrical pin profile was chosen. The tool performed the welding process normal to the plates and had no tilt angles. The welding process was performed using a vertical milling machine (Model M3). The tool rotated clock-wise. The welding parameters were modified to obtain successful weld as shown in Table 4. It should be noted that choosing the welding parameters was based on the results of the other researchers, the mechanical properties of the base metal, the experience gained from previous work, and the condition of the workpiece after welding.

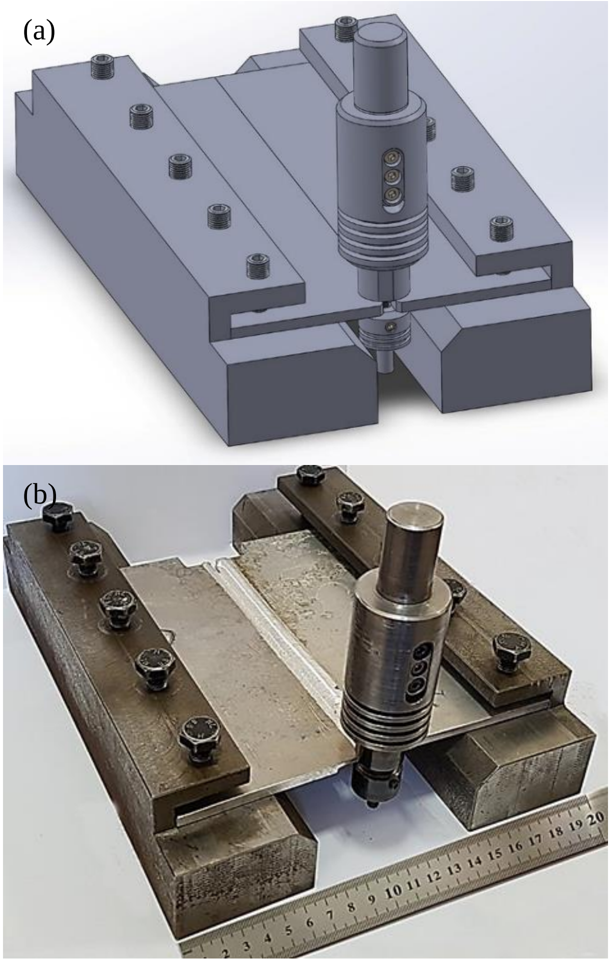

Fig. 2. The image of the floating bobbin tool and its fixture; a) Schematic Image and b) The real picture.

After welding, to ensure the integrity of the welded parts and to ensure that they are free from defects, non-destructive visual inspection and x-ray radiography were performed on the welded samples.

For microstructural examinations, the samples were prepared using 400 to 2000 sandpapers. The samples were etched by chloride alcoholic solution with a mixture of 5g $FeCl_3$, 2cc HCl and 95cc C_2H_2OH for 10 seconds at room temperature. After preparation, the samples were imaged by optical microscope and scanning electron microscope (TESCAN-VEGA 3).

The mechanical properties of the sample were evaluated by tensile and micro-hardness tests. Transverse tensile strength test was performed using universal tensile tester in accordance with ASTM E8 standard. In this test, the strain rate of the device was selected as 2 mm/min. Tensile samples were prepared in subsized dimensions, thus the gage length was 25 mm. The fracture morphology of failed tensile samples was observed by SEM, after tensile tests. The hardness of the samples was evaluated through vickers micro-hardness test via a DHV-1000 hardness tester. The test used samples from the metallographic evaluation that had a good surface smoothness. In order to determine the hardness profile of the weld region, hardness measurements were performed on the cross-section of welds. To this end, the applied force and its duration were selected 1 kg and 15 seconds, respectively.

3. Results and Discussion

The most widely used and essential method for the initial evaluation of welded workpiece sample is the non-destructive evaluation by visual inspection. Using this method, the surface defects of the workpieces was revealed. Therefore, before performing any other destructive or non-destructive tests, the samples were carefully evaluated by visual inspection. In the SRFSW, the tool consisted of two shoulders that were in contact with the face and back of the workpiece. So the surface of the face and back of the workpiece done by SRFSW was similar to the ones done via CFSW. Due to the change in welding parameters to obtain the desired and flawless joints using the SRFSW, the apparent success of the welding process was evaluated by visual inspection.

Figure 3 presents some samples after SRFSW. In this process, as in the CFSW method, increasing the rotational speed of the tool and decreasing the tool progress speed increases the heat input to the weld region. Subsequently, this increase in temperature results in plasticizing the workpiece and facilitates its flow. It is noteworthy that overheating also impedes the desired flow of the material and therefore the heat input should be controlled by changing the welding parameters.

Table 4. welding parameters applied in this study

No.	Tool transverse speed (mm/min)	Tool rotation speed (rpm)	Description
1	24	900	Lack of joining due to insufficient material flow
2	18	900	Failure to weld the bottom of the plate due to insufficient heat in that region
3	18	1120	Excellent welding procedure but pin failed
4	18	1120	Excellent weld, free from apparent defects
5	18	1400	weld optimization in terms of mechanical properties

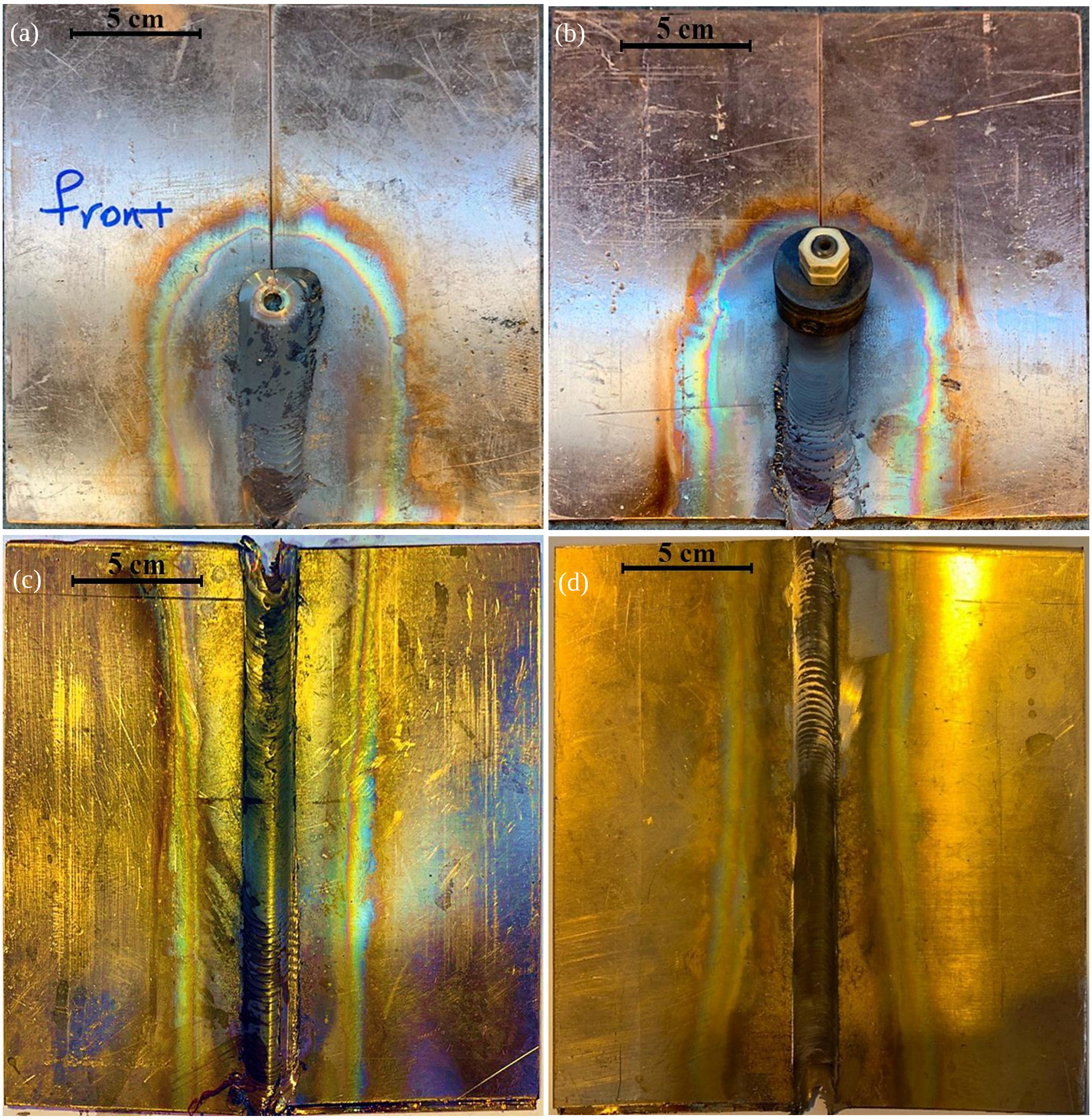

Fig. 3. Images of welded samples; Failed Cu-Cu joining defects (sample No. 3): a) Workpiece face, b) Workpiece back; Successful Cu-Cu joining (sample No. 4): c) Workpiece face, d) Workpiece back.

On the other hand, the pinching gap (distance between the shoulders) in the SRFSW method has a role similar to that of the vertical force applied in the CFSW process. Hence, a decrease in the shoulder pinching gap will be associated with increased forging force. If the pinching gap is more than the thickness of the sheet, there is probably no effective contact between the shoulders and the surface of the work-piece, so the shoulders cannot play their role in this process. On the other hand, too much reduction of pinching gap leads to excessive shoulder entry in the base metal, resulting in sheet tearing and failure. The pinching gap also has an optimum value, which is determined by experience, base metal ductility, tool transverse speed as well as tool rotation speed.

As shown in Table 4, welding samples No. 1 and 2 was not successful, the main reason of which was the lack of sufficient frictional heat production for the proper flow of the workpiece material and its joining as a result of the stir. By changing the welding variables such as the tool transverse speed and the tool rotational speed, the initial steps of welding sample 3 were successful, but the welding process was stopped due to the failure of the pin. The pin, which was used several times to run the process, failed from the end of one of the threads. Fig. 3(a) and 3(b), show the face and back of sample 3. Pin failure stopped the process. One of the causes of pin failure and stopping the welding process was the very high hardness of the tool and occurring fatigue. By changing the heat treatment cycle applied to the pin and increasing the diameter of the tool's shoulder, the desired joint was obtained (sample number 4) and the image of its face and back are presented in Fig. 3(c) and 3(d). As can be seen, there were no signs of non-uniformity or discontinuity on either surfaces of the workpiece. In the case of the surface success of the welds, in order to ensure that no internal defects were formed during the process and the welding process was free from the defect, a non-destructive radiographic test was performed, the result of which are presented in Fig. 4. There were no defects in the radiograph. The mixing of the two parts was well done in the middle zone of the joint and there was no sign of lack of penetration, tunneling, cracks and any internal defects.

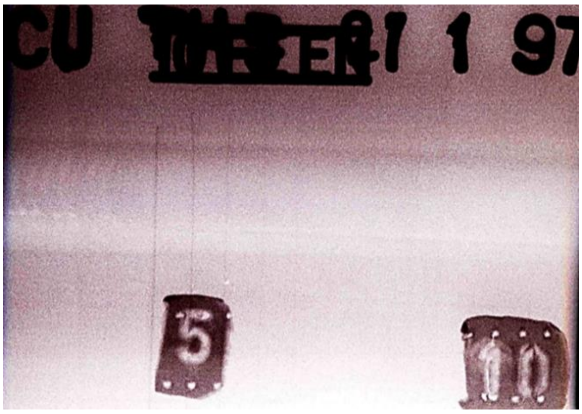

Fig. 4. Cu-Cu joint radiograph (sample No. 4).

In FSW - due to the concentrated severe plastic deformation and increase in temperature of the stirred zone - severe changes in the microstructure and its improvement compared to the base metal were observed, especially in the stirred zone. Fig. 5 shows the metallographic images of the microstructure of the weld. In these images, changes in grain size from the base metal to the stirred zone are evident. The heat-affected zone (HAZ) had a microstructure similar to the base metal but were larger in grain size. This zone merely experienced one thermal cycle, yet did not undergo any plastic deformation. Between the HAZ and the stirred zone, there was a zone where the grain size was larger than the grain size in the stirred zone but smaller than the ones in HAZ. This zone is called the thermomechnically affected zone (TMAZ). The plastic deformation in the (TMAZ) was less than the necessary amount that was necessary to commence dynamic recrystallization. However, due to its vicinity to the stirred zone, its temperature was higher than the temperature of the HAZ. Thus, the TMAZ consisted of a high density of sub-boundaries. Most of the microstructural changes compared to the base metal were in the center of the weld, i.e., the stirred zone. This zone consisted of ultra-fine equiaxed grains. The impressive grain size refinement in the stirred zone was obvious. The main reason for the drastic grain refinement in this zone compared to base metal was attributed to the dynamic recrystallization. This phenomenon has been reported by other researchers [17-20, 24-26, 33].

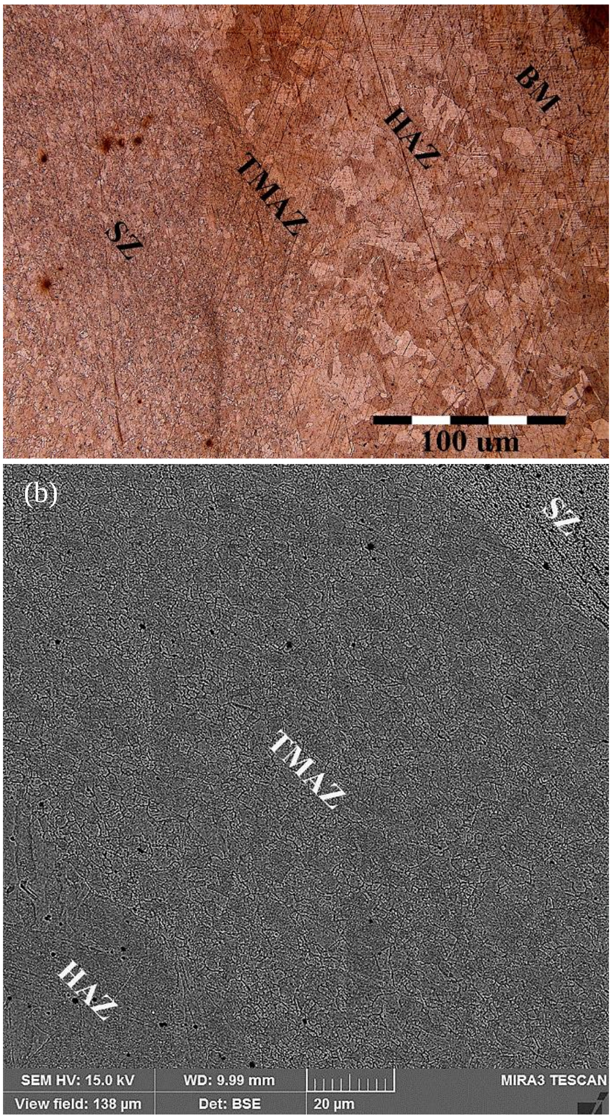

Fig. 5. Microstructure of different joint areas (sample No. 5); a) optical microscope micrograph; and b) electron microscope micrograph.

In order to evaluate the tensile strength of the samples, the tensile test was performed on the base metal and the welded samples. The stress-strain diagram and test results are presented in Fig. 6 and Table 5, respectively. The tensile strength of the base metal was about 226 MPa. The SRFSW of this alloy had acceptable results in terms of tensile strength and strain. Thus, the tensile strength and fracture strain of the commercial pure copper joint for sample 4 were 158.5 MPa and 13.4%, respectively.

Accordingly, the efficiency of this joint- which was the result of dividing the tensile strength of the welded sample by the tensile strength of the base metal- was 70.2%. In order to evaluate the possibility of improving the mechanical properties of the weld, sample No. 5 was welded at the tool transverse speed of 18 mm/min and tool rotational speed of 1400 rpm. The mechanical properties of this joint were better than the previous samples, so that the joint efficiency of this sample was calculated to be 86.4%.

Table 5. Mechanical properties of base metal and welded work-pieces

Sample	Tensile strength (MPa)	Fracture strain	Joint efficiency (%)
Base metal	225.9	70	-
Weld No. 3	153.1	6.7	67.8
Weld No. 4	158.5	13.4	70.2
Weld No. 5	195.2	26.8	86.4

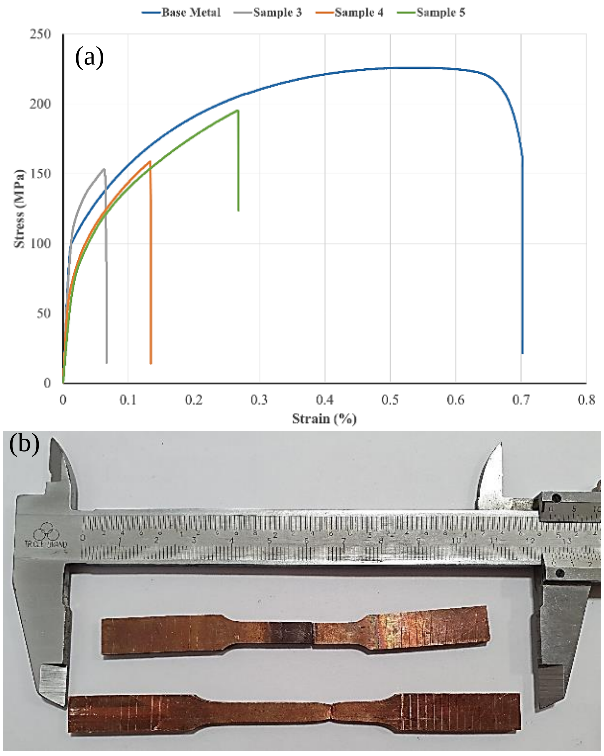

Fig. 6. a) Stress-strain curve of welded commercial pure copper; and b) base metal and welded sample No. 5 after tensile test.

The fracture site of the welded sample No. 5 after the tensile test was in the heat-affected zone, on the retreating side (Fig. 6(b)). Usually the weakest zone in acceptable joints done by friction stir welding was the heat-affected zone. As can be seen in the microstructural images in Fig. 5, in different welding areas, the largest grain size belonged to the heat-affected zone. Therefore, the lowest strength belonged to this zone and the probability of fracture in this zone was higher. This result was stated and confirmed by other researchers as well [22, 23, 34]. In order to assess the quality of the created joints, their mechanical properties were compared with previous studies. A summary of previous research on fusion welding and solid-state welding of copper is presented in Table 6.

High heat transfer coefficient, high thermal expansion coefficient and its undesirable freezing microstructure as a result of segregation were among the main reasons for low weldability of copper in conventional fusion welding method. However, studied material had good weldability during solid-state welding by FSW. As mentioned before, during FSW, in addition to creating a defect-free joint and improving the microstructure, the desired mechanical properties were obtained. A comparison of the results of previous research mentioned in Table 6 also confirms this very issue. By comparing the mechanical properties of the similar joints of commercial pure copper by SRFSW method (Table 5) with previous research (Table 6), important results were obtained:

1. The mechanical properties of copper welded by fusion welding methods were lower than the mechanical properties of copper welded by FSW.

2. The efficiency of the similar joints of welded copper via CFSW after about three decades of the emergence of this method and increasing advances in this field under certain conditions - such as excessive vertical force or rapid cooling of the welded workpiece - reached the strength of the base metal.

3. In this study, using the new technique of SRFSW with low research history, the efficiency of 86.4% was obtained for similar joint of commercial pure copper; which was more than the efficiency of fusion welding and was comparable to the results of the CFSW method.

4. The strain fracture of the similar joints created by SRFSW was usually more than the one done by fusion welding and CFSW.

Table 6. Summary of mechanical properties of previous studies on copper welding

BM	Thickness (mm)	Welding method	BM tensile strength (MPa)	Weld Tensile strength (MPa)	Weld fracture strain (%)	Joint efficiency (%)	Description	Reference
		FSW		221	-	86.7		
Cp-Cu	4	EBW	255	214	-	84		[16]
Cu	2	FSW	273	231	1.2	84.6		[18]
Cp-Cu	2	FSW	266	266	20	100	extra high normal force	[3]
P-Cu	3.1	FSW	279	220	48	78.9		[1]
P-Cu	3	FSW		282	16.4	~100		[19]
		FSW		194	22.8	92		
P-Cu	3	TIG	212	168	12.3	79		[27]
P-Cu	5	FSW	354	304	40	85.9	True stress & true strain	[25]
		MIG		190		69		
Cu-T2	4	Hybrid	276	204	-	74		[35]
Cp-Cu	2	FSW	270	248	28	91.8		[36]
P-Cu	5	FSW	334	216.9	9.2	65		[37]

As can be seen in Fig. 6(b), the fracture site of the tensile test sample done by SRFSW was in the heat-affected zone. For a more detailed study of the fracture mechanism, the fracture surface of the samples was evaluated by scanning electron microscopy (Fig. 7). Due to the large number of dimples drawn at the fracture surface of the base metal, the slip fracture mechanism, or in other words, the ductile fracture, was the cause of the fracture of the workpiece. But in the fractured surface of the welded sample, some of the dimples were deformed, with regions free of common signs of fracture mechanisms. Thus, the fracture mechanism of the welded samples is a combination of the soft and brittle fracture mechanism. Thus, the simultaneous effect of the two mechanisms of ductile and brittle fractures in the welded parts justified the lower ductility of these parts compared to the base metal.

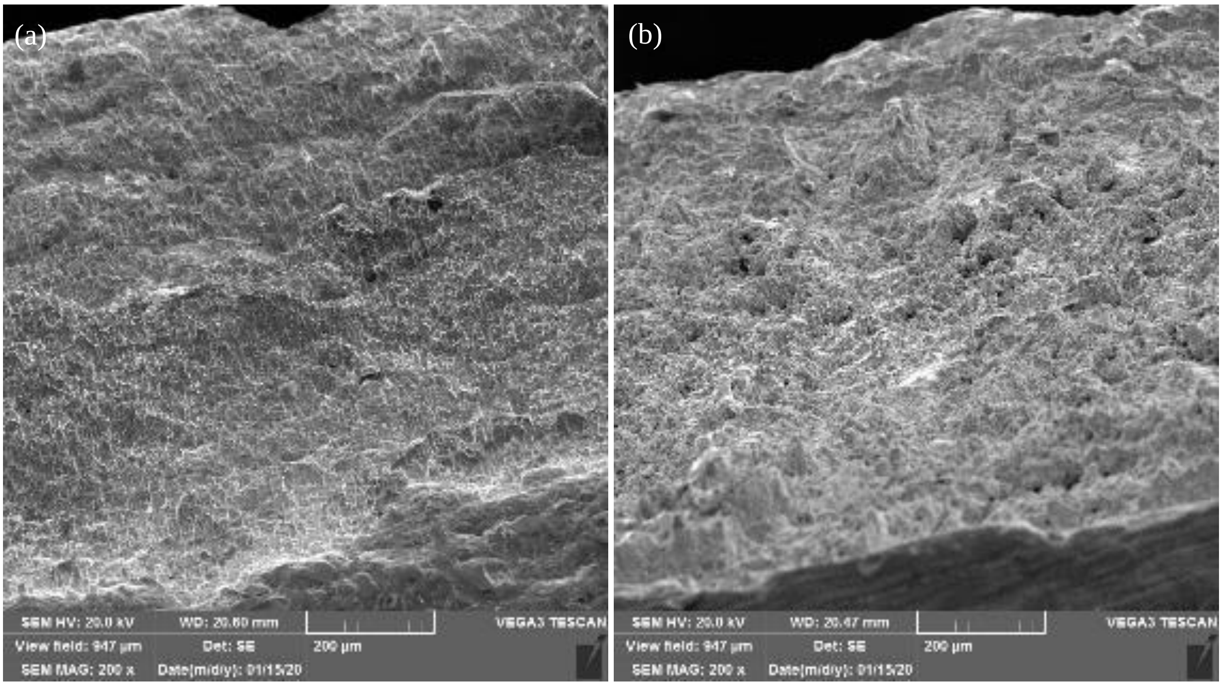

Fig. 7. Fractographs of the broken tensile sample: a), c) and e) base metal; b), d) and f) welded Sample.

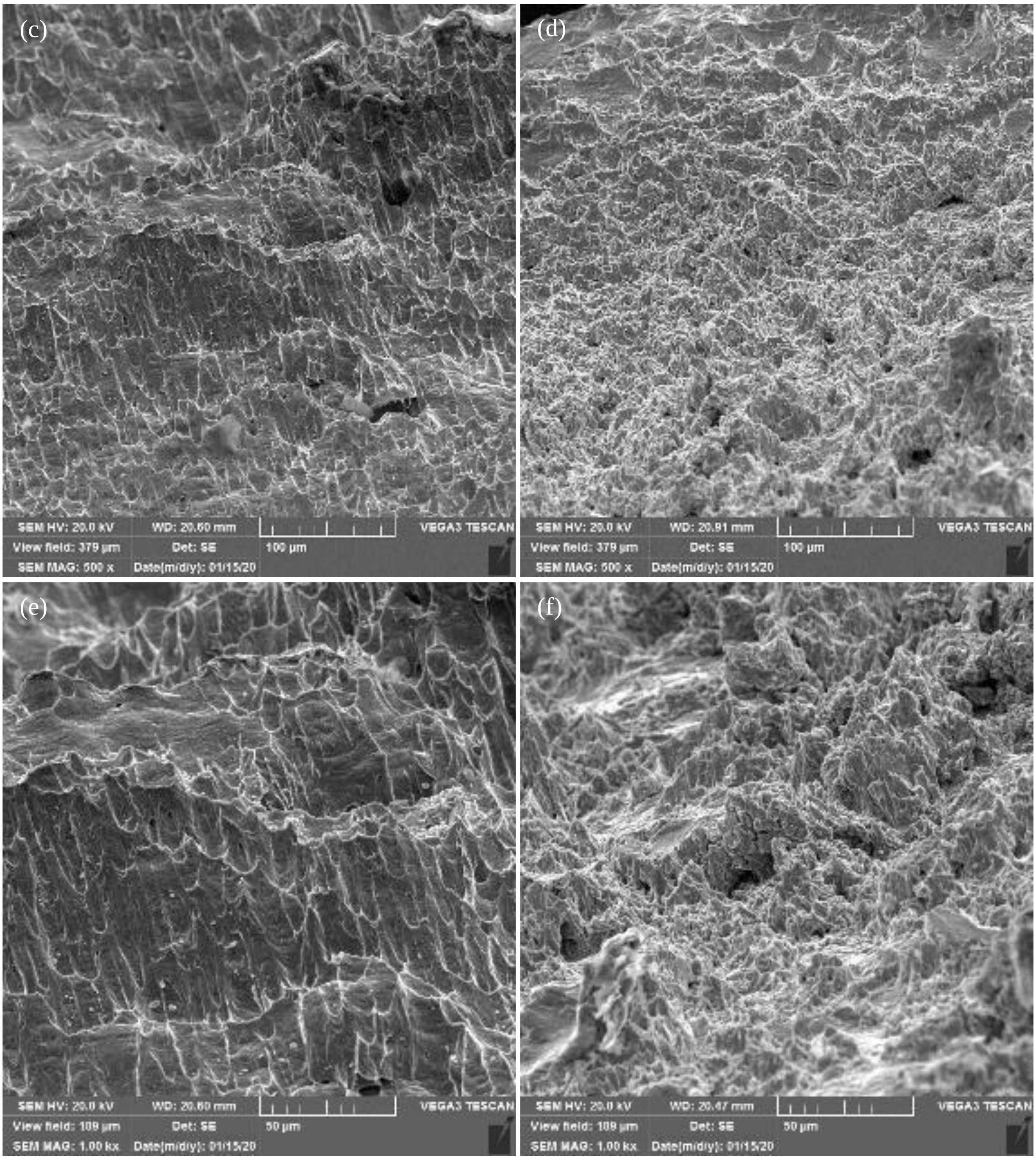

Fig. 7. Continue.

Micro-hardness profiles of the transverse section of the welded samples by SRFSW is shown in Fig. 8. It is observed that the micro-hardness distribution curve is asymmetric with respect to the center of the stirred zone.

The asymmetry of the micro-hardness distribution in turn depends on the asymmetry of the plastic flow in the two advancing and retreating sides. Since the amount of plastic strain in the advancing side is higher than the retreating side, higher heat caused by plastic deformation is generated in this region. Higher temperatures in the advancing side results in more grain growth in that region, resulting loss of micro-hardness in the advancing side compared to the retreating side [38, 39]. Furthermore, in the SRFSW if on the face of the work-piece (upper part of the workpiece thickness), the right side is retreating; on the back of the work-piece (bottom half of the work-piece thickness) the right side is advancing. In this case, the asymmetry of the hardness profile for the top half and bottom half is opposite.

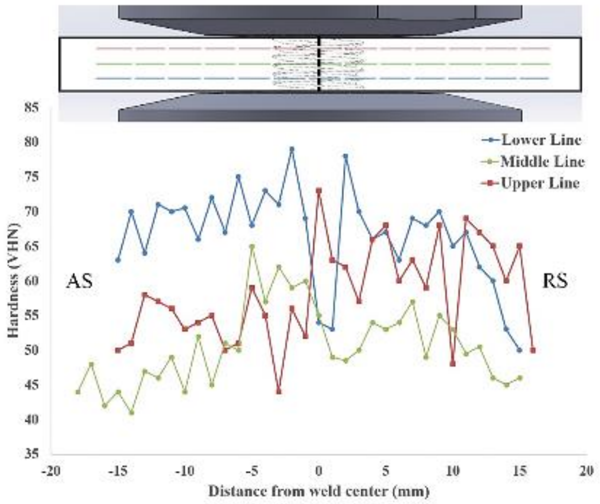

Fig. 8. Microhardness profile of the joint.

On the other hand, due to the shape of the shoulders and how they connected to the tool, the upper shoulder of the tool was warmer than the lower one (two chillers were designed on the lower shoulder). Therefore, in the adjacent area to the lower shoulder, which had a lower temperature, it was expected that the grain size changes would be more severe and therefore harder than the upper surface of the workpiece. In addition, moving away from the surface of the workpiece towards the inside of it, the impact of the shoulders on the amount of deformation, decreased. Therefore, in the middle of the workpiece, which rotation and profile of the tool were the only factors of deformation of the material, experienced less deformation compared to the upper and lower surface of the workpiece.

4. Conclusions

In this study, the commercial pure copper was successfully welded via SRFSW method. To achieve the desired joint, the tool rotational speed and the tool transverse speed were selected to be 1400 rpm and 18 mm / min, respectively. Welded samples were subjected to destructive and non-destructive tests in order to assess the quality of the joints, and the following results were obtained:

- A sharp decrease in grain size in the stirred zone, compared to the base metal, was a major factor in the optimal mechanical properties of the joint.
- The tensile strength, fracture strain, and joint efficiency obtained for SRFSW samples were greater than those welded via fusion welding methods such as EBW, TIG, MIG and Hybrid Welding.
- Following the transverse tensile test, a fracture was caused in the welded sample when it was placed in the heat-affected zone, indicating the high quality of the weld. Since grain growth in the heat-affected zone was inevitable, this zone was considered to be the weakest weld zone in terms of mechanical properties.
- Examination of the fracture surface of welded samples showed that the fracture mechanism was a combination of ductile and brittle fractures and the ductile fracture mechanism was predominant.
- The greatest hardness was attributed to the advancing region of the adjacent area to the lower shoulder. In this region, the weld metal experienced the lowest temperature. In contrast, the lowest hardness was found in the middle zone of the weld.

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اتصال مس خالص تجاری به روش جوشکاری اصطکاکی اغتشاشی خودواکنشی

سوفیا پاکدامن و امین ربیعی‌زاده

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چکیـــده

ورق‌هایی به ضخامت ۳ میلیمتر از جنس مس خالص تجاری با استفاده از ابزار دوکی شکل شناور، جوشکاری اصطکاکی اغتشاشی شدند. اثر متغیرهای مختلف فرآیند نظیر سرعت پیشروی و سرعت چرخش ابزار به منظور ایجاد اتصالی با خواص مطلوب مورد بررسی قرار گرفت. اتصالی عاری از عیب در سرعت چرخش ۱۴۰۰ rpm و سرعت پیشروی ۱۸ mm/min با فاصله بین شانه ۲/۷ mm بدست آمد. پس از اجرای فرآیند جوشکاری، کیفیت قطعات جوشکاری شده به روش‌های غیرمخرب بازرسی چشمی و رادیوگرافی تأیید شد. نتایج آزمون کشش عرضی نشان داد که راندمان اتصال جوش، پس از جوشکاری ۸۴/۶ ٪ است که نسبت به راندمان اتصال روش‌های ذوبی بیشتر است. استحکام اتصال ایجاد شده به حدی بود که محل شکست قطعات بعد از آزمون کشش، در ناحیه متأثر از حرارت بود. از طرفی اندازه دانه جوش به طور چشمگیری از فلز پایه کمتر است. کمترین سختی در حدود ۴۰ VHN مربوط به ناحیه میانی جوش است و بیشترین سختی در ناحیه مجاور به محل عبور شانه پایینی ابزار در حدود ۸۰ VHN اندازه‌گیری شد.

واژه‌های کلیدی: جوشکاری اصطکاکی اغتشاشی خودواکنشی، مس، ابزار دوکی شکل شناور، راندمان اتصال، خواص مکانیکی