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The influence of rotational speed on welding strength and surface roughness of friction stir welded copper

Salina Budin*, Koay Mei Hyie, Normariah Che Maideen

School of Mechanical Engineering, College of Engineering, Universiti Teknologi MARA, Cawangan Pulau Pinang, 13500 Kampus Permatang Pauh, MALAYSIA.
*Corresponding author: salinabudin@uitm.edu.my

KEYWORDS

Friction stir welding
Copper
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Welding strength
Surface roughness

ABSTRACT

Due to the properties of copper which exhibited high thermal conductivity and high expansion coefficient, welding of copper by fusion welding process is very difficult. Friction stir welding (FSW), a solid state welding technique is seen to be a possible alternative which could have overcome these shortcomings in order to produce zero-defect weld. FSW involves the penetration of rotating tool and prolonged by a pin into a metal plate. The process is followed by allowing speed to weld the metal plate. In this study, the influence of rotational speeds, welding strength and surface roughness of frictional welded copper using conventional milling machine are investigated. The results demonstrated that the welding strength increased as the rotational speed increased. The highest welding strength of 210 MPa was reported at the rotational speed of 1790 rpm. An increased in the rotational speed to 2540 rpm resulted in an excessive frictional heat which exposed the sample to overheating and heavy deformation that may have had caused an improper bonding. A similar trend was observed on the surface roughness where the surface roughness decreased at a rotational speed of 1790 rpm. The study also revealed promising results in defect-free welding of copper by FSW.

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1.0 INTRODUCTION

Copper is one of the most important metal and is widely used as an engineering structural material (Panaskar and Terkar, 2017). Pure copper is tough, malleable, ductile, has high corrosion resistance and exhibits excellent heat and electrical conductivity (Shankar and Chattopadhyaya, 2020). Copper and copper alloy are commonly used in automotive industry parts such as radiator, hydraulic equipment, gear, bearing, valves, power distribution, brake lining and all kinds of industry joint. It is also used for navigation instrument, water tubing, valves, fittings, heat exchangers, chemical equipment and bearing. In assembling copper product, numerous joining methods were used such as arc welding, brazing, ultrasonic welding and electron beam welding. Unfortunately, these conventional fusion welding processes of copper family have some difficulties. Welding of copper is usually difficult due to its thermal properties which exhibited high thermal diffusivity. As compared with other metals such as steels and nickel, the thermal diffusivity of copper is higher with approximately 10 to 100 times. The heat dissipates faster than almost any other materials thus resulting in a low welding quality (Agapiou et al., 2020).

In order to overcome the above-mentioned problems, friction stir welding (FSW) technique is seen as a potential option. In FSW, the joining is taking place in a solid state. This joining invention process was invented in 1991 by The Welding Institute (TWI) in United Kingdom (Shen and Chen, 2015). Since the joining occurs in a solid state condition, numerous advantages are observed as compared to conventional fusion welding. Common defects which are caused by melting during the fusion welding such as grain boundary cracks and porosities are eliminated in FSW. FSW also reduces the presence of distortions and residual stress due to its lower welding temperature (Karrar et al., 2020). Moreover, it can be considered as a low-cost welded joint method because of its lower power consumption, zero-joint edge preparation before welding and no shielding gas is required which leads to a greener welding operation.

In FSW, a special tool consisted of shoulder and pin was designed. During the FSW process, the tool is rotated and brought into contact with metal plates. Due to the contact, the friction which has occurred between the tool shoulder and metal plates will generate a heat thus softening the metal plates (Budin et al., 2019). When the rotating tool travels along the joining line, the heated and softened metal plates will mechanically be blended and forged the work materials. As a result, a joint is produced in a solid state (Singh et al., 2018).

The process of the FSW can be divided into 4 phases that are plugging the tool phase, dwelling phase, welding phase and lastly, retract phase (Chowdhury et al., 2021). The first phase is where the rotation tool is brought into contact with the work metal. In the second phase, the frictional heat is generated between the tool and the butt joint plate hence causing the metal molecules at the plate to be softened and mixed below the melting point. The third phase begins when required heat is achieved. The feed rate is then applied thus causing the tool traversing along the butt to join the plate. Finally, during the fourth phase, the tool is moved out from the welded zone in an upward vertical movement.

A number of past studies has emphasized on the important factors to produce a zero-defect weld in FSW. A study by Singh et al. (2018) had highlighted that the geometry of tool, welding parameters and joint configuration were the important factors in determining the temperature distribution and flow pattern of the work material. The process parameters such as tool rotation rate, traverse speed, spindle tilt angle was strongly affecting the mechanical and metallurgical behaviours of joints. Hence, these were crucial in producing an ideal and zero-defect weld. Many studies in relation to FSW have been conducted to investigate the correlation of various processing parameters towards the quality and characterization of joining including final microstructure and mechanical properties. Most of the findings were established in an empirical model that were able to assist and benefit the real manufacturing areas (Liu et al., 2019). Heidarzadeh and Saeid (2013) in their works had developed a numerical model in predicting mechanical properties of friction stir welded of pure copper joints. The optimal welded parts were achieved at the rotational speed ranges from 700 to 1100 rpm and welding speed ranges from 50 to 100 mm/min. In addition, the authors had also claimed that the application of axial force should be best set between the range of 1.5 to 2.5 kN. In a study by Milicic et al. (2016), the researchers had studied and analysed the weldability of pure copper using FSW process. The authors proved that the effects of shoulder face of the tools produced a thermal energy in preheating the material and creating conditions for a quality welding. Therefore, the study suggested that during the mixing process, friction was formed by the tool and caused plastic deformation of the material and a fine-grained seam structured was produced.

Besides that, Nagabharam et al. (2018) conducted a study in determining the optimum mechanical properties of copper produced by FSW. The results showed that the joints fabricated using a rotational speed of 910 rpm and a welding speed of 30 mm/min exhibited the highest tensile strength of approximately at 217 MPa. In another studies, Murugan and Thirumalaisamy (2018) had welded copper and bronze plates by using FSW at various rotational speeds and a constant welding speed. It was reported that the increased in rotational speed had reduced the microstructural size and consequently increased the microhardness. Akinlabi et al. (2017) on the other hand had evaluated the hardness and tensile strength of welded copper using FSW at rotational speeds of 1200 rpm to 2000 rpm. The maximum tensile strength was observed at a rotational speed of 1600 rpm. However, the highest hardness was exhibited on the sample welded at 2000 rpm.

In short, the motion in using FSW involved the processes of rotating of tool and feeding of the work piece. This phenomenon is similar to the principle of milling process. Thus, a conventional milling machine with appropriate tools, jigs and fixtures could become an alternative machinery to FSW. This invention of milling machine mimics FSW process and will offer many advantages to the industry. The cost of manufacturing will be reduced resulting in products with lower-cost. Therefore, this work aimed to study the effects of rotational speeds in the weldability of frictional welded copper C10200 by using a conventional milling machine. Copper C10200 is also known as Oxygen-free High Conductivity (OFHC) copper. There are limited works related to the weldability of copper C10200. The material is selected as it possessed a variety of engineering components such as vacuum tubes, gutters, gaskets, heat sinks and printing rolls.

2.0 METHODOLOGY

2.1 Material

Copper alloy with a grade of C10200 or commercially known as Oxygen-free High Conductivity (OFHC) copper was used as a welding sample with the dimension of 150 mm (L) X 50 mm (W) and 4 mm (T). The composition and the mechanical properties of the sample were summarized in Table 1.

Table 1: Composition and mechanical properties of work material.

Composition	99.5wt% Cu, 0.499 wt% Ag, 0.001wt% O
Tensile Strength	250 MPa
Thermal Conductivity	370 W/mK
Modulus of Elasticity	117 GPa

2.2 Tool Design

The foremost features of FSW tool were the shoulder and pin (Kumar et al., 2021). The shoulder played a crucial role in generating frictional heat and facilitating the work material around the tool to undergo plastic deformation. In addition, shoulder was also responsible in ensuring that the softening of work material being remained in the welded zone. On the other hand, the tool pin acted as a stirrer in order to stir and blend the work material. As a result, a suitable tool with appropriate pin and shoulder had been designed. H13 steel was used in the fabrication of FSW welding tool. The consideration in selecting a tool material was based on its melting point. Primarily, the melting point of the tool material should be higher than the work material. Hence, the melting point of H13 steel and copper C10200 were set approximately at 1427°C and 1083° C respectively. The shoulder diameter of the tool was of 20 mm. The surface concave was set at 8˚ and the pin was tapered with 15˚ from 4.55 mm diameter on the base. The isometric view of the tool design is shown in Figure 1. The length of the pin was fixed at 2.7 mm with 0.3 mm clearance.

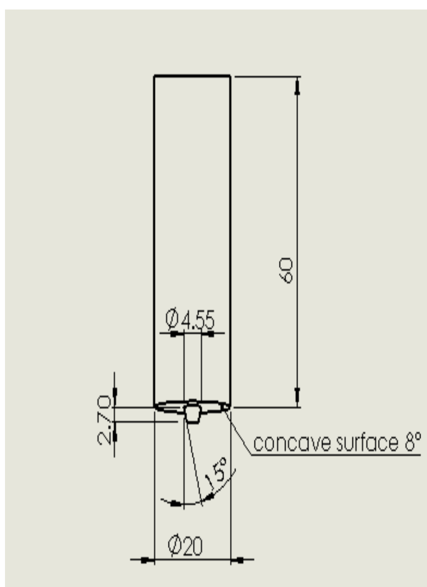

Figure 1: Tool design.

2.3 Friction Stir Welding

FSW was conducted using a conventional Turret Milling Machine (CY-GH260). A special welding jig and fixture was designed to hold the samples. Single pass welding butt joint procedure was employed to weld the copper samples. The rotational speed was set at five different speeds which were at 1000 rpm, 1270 rpm, 1630 rpm, 1790 rpm and 2540 rpm. The ranges of rotational speed used in this work were based on previous literature (Akinlabi et al., 2017) and the limitation setting of the milling machine. The welding speed was kept constant at 218 mm/min during the process. The direction of welding was normal to the rolling direction. The frictional heat which was generated from the rotation and the advancing motion of the tool pin and metal plates, had softened the metal plates which was closed to the tool. As a result, the softened metal plates were stirred, blended and forged around the rotating tool. When the metal plates had cooled down, a solid-state welding was created.

2.4 Analysis

The weldability of copper C10200 was verified in terms of external visual inspection, welding strength, surface roughness and the percentage of weight loss. The external visual inspection was conducted upon the completion of FSW process in order to identify the welding defects. The inspection was carried out using a lower power microscope (MEIJI Techno ML8100) at a magnification of 3X. Meanwhile, the welding strength was determined by using a Shimadzu Autograph AG-IS Universal Testing Machine. The equipment was operated at a full-scale load range of 50kN with the gauge moving speed and sampling rate were set at 5 mm min^{-1} and 20 pts s^{-1} respectively. The test was conducted at room temperature. Later, the maximum strength was obtained from the stress-strain curves. In order to ensure the consistency of the data, the testing was replicated three times and the final welding strength was obtained from the average value. As for the surface roughness, it was measured based the arithmetic mean deviation (Ra) parameter using a SURFTEST SJ-210 Surface Roughness Tester. The surface roughness was measured along the welding zone. Five data were collected and the average value of surface roughness was calculated. The weight of the samples was measured using an electronic weighing scale (Oxford Precision OXD-844-2220K). The percentage of weight loss in the samples was calculated using Equation (1).

$$\%\ of\ losses = {}^{mass_a}/_{mass_i}\ X\ 100\% \tag{1}$$

where $mass_a$ is the mass of sample after welded and $mass_i$ is the initial mass of the sample.

3.0 RESULTS AND DISCUSSION

3.1 Welding Inspection

Figure 2 showed the typical weld appearance of welding for the samples welded at different rotational speeds. At the rotational speed of 1000 rpm, there was no appearance of welded occurred. As the rotational speed increased to 1270 rpm, partial welded was observed. Similarly, when the rotational speed was increased to 1630 rpm, the percentage of welded welding area was also increased. However, an irregular welded appearance was noted on the welded surface. The complete welding was observed on the samples with rotational speeds of 1790 rpm and 2540 rpm. It was also noted that the welding pattern was slightly rough at the rotational speed of 2540 rpm as compared to the rotational speed at 1790 rpm. Numerous flashes were also seen along the sides of welded areas.

At the very lower rotational speed, less heat input was recorded as a result of the inadequate reaction temperature and insufficient reaction of the material. Thus, poor welding was obtained due to inappropriate plastic deformation occurred in the stirring zone. In contrast to higher rotational speed, excessive stirring by the tool pin had caused larger plastic deformation and grain growth was visible at the welding zone (Zhang et al., 2019). The similar results were associated with the findings from Akinlabi et al. (2017) which had reported that copper samples were not well-bonded samples at the rotational speed of 1200 rpm. The authors had also remarked that the optimum welding was achieved at the rotational speed of 1600 rpm.

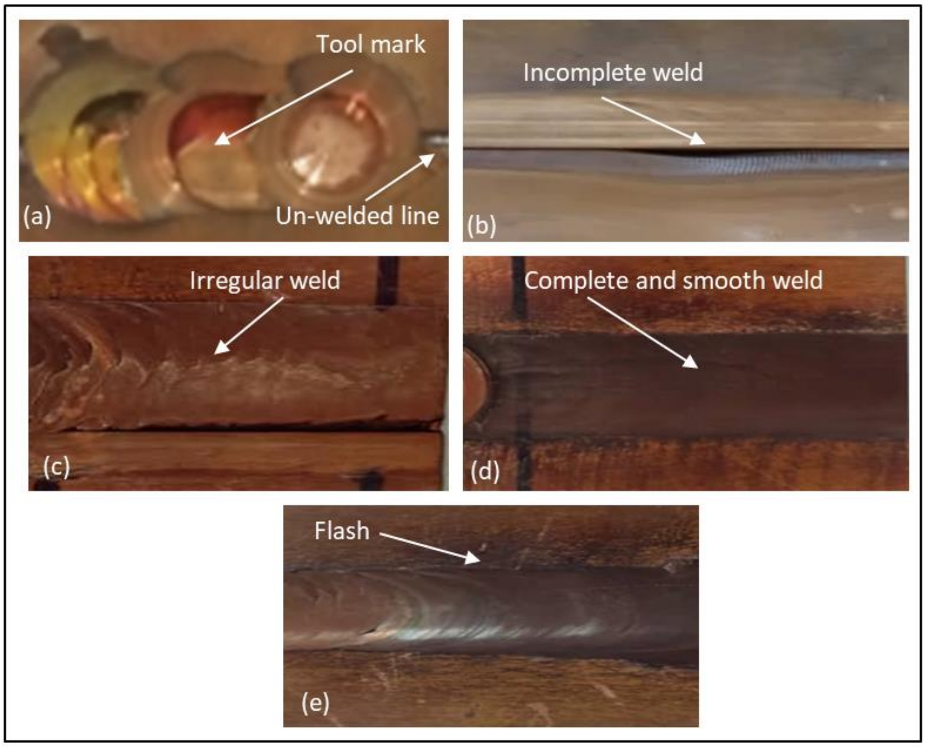

Figure 2: Welding appearance. A) 1000 rpm, b) 1270 rpm, c) 1630 rpm, d) 1790 rpm, d) 2540 rpm.

3.2 Welding Strength

Figure 3 displayed the plots of the welding strength in relation to the rotational speeds. As illustrated in the figure, as the welding strength increased, the rotational speed increased. The highest welding strength was recorded at the rotational speed of 1790 rpm, which was approximately at 210 MPa. At high rotational speed, appropriate frictional heat was generated and consequently increasing the plasticity region. As a result, high welding strength was achieved. In other noteworthy, further increases on the rotational speed to 2540 rpm had led to the reduction in welding strength at approximately 159 MPa. The results obtained in this work were consistent with previous findings by Khan et al. (2017) and Salih et al. (2015). In contrast, at low rotational speed, less frictional heat was generated hence creating insufficiency for the plasticity of the work material to increase. Thus, inefficient consolidation and inadequate mixing occurred which had ended up in the poor joint. In oppose to that, at high rotational speed, more frictional heat was generated and consolidated to appropriately weld. Nonetheless, at extremely high rotational speed, excessive frictional heat was generated causing overheating of the metal plates. It was noted that exposure to overheating conditions would have caused heavy deformation and excessive grain growth thus reducing the welding strength (Sucharitha et al., 2021).

The results had shown that the highest welding strength was obtained at a tool rotational speed of 1790 rpm. At this rotational speed, an adequate and optimum heat was generated that had aided the plasticized work material to flow freely and mechanically blended. Although the optimized welding strength value was slightly lower than the tensile strength of the based copper material, it was still considered a strong weld since the weld did not penetrate through the whole work-based thickness (Sucharitha et al., 2021).

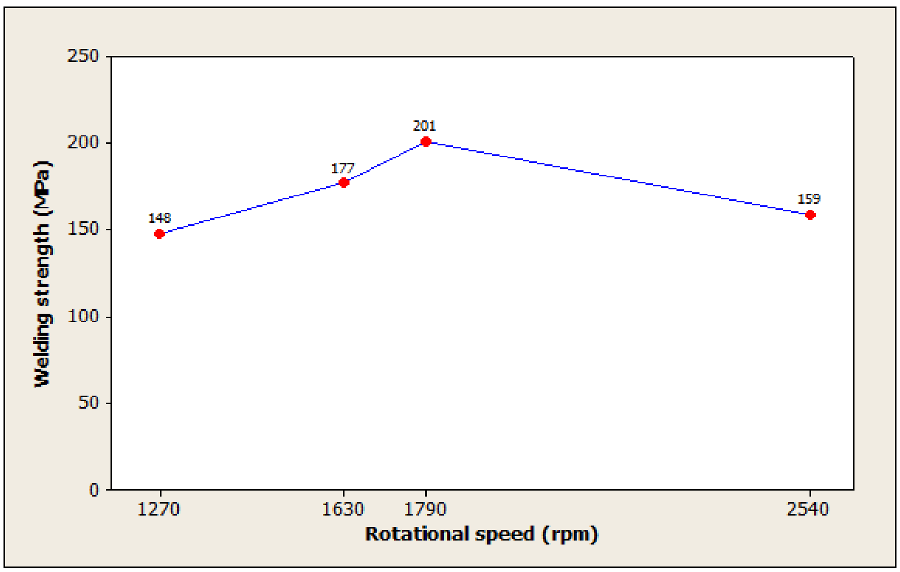

Figure 3: Welding strength in relation to the rotational speed.

3.3 Surface Roughness

Surface finishing is one of the important features in post-welded parts. High surface roughness may have required an additional surface finishing process that would have increased manufacturing cost. Figure 4 displayed the plots of surface roughness in relation to the rotational speed. Based on the results, it was clearly seen that the surface roughness decreased as the rotational speed increased. The optimum surface roughness was observed on the sample that was prepared at a rotational speed of 1790 rpm. At this rotational speed, the surface roughness was minimum which is at 0.75 µm. However, as the rotational speed continued to increase to 2540 rpm, the surface roughness was increased to 1.4 µm. The result was consistent with the findings from Thamizhmanii et al. (2013). By raising the rotational speed, more frictional heat was generated which improved the weldability, and the surface roughness. In contrast to that, at excessive rotational speed, massive heat and high tool pin stirring had caused extreme plastic deformation on the work material, resulting in an irregular and rough welding surface.

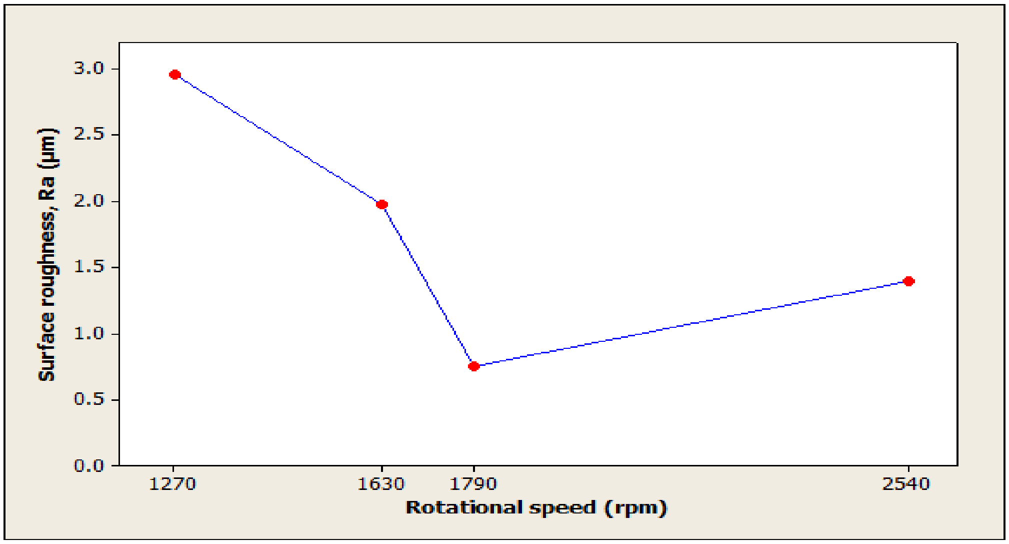

Figure 4: Surface roughness in relation to the rotational speed.

3.4 Weight Loss

The weight loss was measured to verify the possibility of material loss during the welding process that could had happened while stirring. During stirring, the work materials were soft and had the ability to splash the work materials forming a flash around the welded zone. The summary of the percentage of weight loss at various rotational speeds was listed in Table 2. The percentage of weight loss was gained from the weight of the metals, before and after underwent the process of FSW. The weight loss was calculated based on the pre and post weights. The results revealed that the percentage of weight loss were consistent regardless at any rotational speed. It was also noticeable that the percentage of the weight lost was minimal at approximately 0.39%. Moreover, the results in weight loss were in accordance with the welding inspection which had spotted the formation of flashes around the welded zone.

Table 2: Weight loss of the samples.

Rotational Speed (rpm)	Percentage of Weight Loss (%)
1270	0.39
1630	0.39
1790	0.39
2540	0.39

CONCLUSION

FSW was conducted on copper C10200 and the effects of different rotational speeds were evaluated. The welding strength and surface roughness were used to characterize the influence of varying rotational speeds. The results of investigation were summarized as follows:

(a) A defect-free weld was observed at a rotational speed of 1790 rpm. At a lower rotational speed, less heat was generated which had led to poor and insufficient welding.

(b) The welding strength increased as the rotational speed increased. The highest welding strength of 210 MPa was reported at a rotational speed of 1790 rpm. An increased in the rotational speed to 2540 rpm had resulted in excessive frictional heat thus exposing the sample to overheating and heavy deformation. These could have had resulted in an improper bonding.
(c) The surface roughness decreased as the rotational speed increased. Despite that, the optimum surface roughness was observed on the sample welded at a rotational speed of 1790 rpm. This was because when the rotational speed was increased to 2540 rpm, extreme plastic deformation was produced on the work material, resulting in an irregular and rough surface.

The outcomes had proven the capability of conventional milling machine as an alternative system for FSW process. These findings would be beneficial for related manufacturing industries in designing and developing flexible and versatile manufacturing systems and processes.

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