Effect of Rotation Speed on Microstructure and Mechanical Properties of Continuous Drive Friction Welded Dissimilar Joints of 6061-T6 Al and Copper

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Abstract: The continuous drive friction welding of 6061-T6 Al and copper was investigated herein. The results show that with an increase in rotation speed, the width of the welded zone was gradually increased with the generation of higher temperatures, and the grain size in the dynamic recrystallization zone on the Al side first decreased and then increased due to the combined effect of heat and force. The microhardness on the bonding surface was significantly greater than that of the base materials due to the presence of intermetallic compounds, and there was a softening zone on both sides of the bonding surface, which was progressively more significant with an increase in the rotation speed. The ultimate tensile strength (UTS) of the welded joints first increased and then decreased with an increase in rotation speed. When the rotation speed was 1000 rpm, the UTS was at its peak value of 212 MPa, which reached 73.1% of the strength of the 6061-T6 Al base material.

Keywords: dissimilar welding; continuous drive friction welding; 6061-T6 Al; copper; microstructure; mechanical properties

1. Introduction

Dissimilar materials joining technology provides an excellent solution to the problem of most industries moving towards using dissimilar alloys to produce components with multiple service properties [1]. In particular, welded structural components made of aluminum alloys and copper combine the electrical and thermal conductivity of Cu with the excellent mechanical properties and relatively low cost of Al [2,3]. This idea has been widely used in the electrical, electronic, and chemical industries, and has great potential for application in new energy vehicles [4–6]. Generally, due to the remarkable differences in physical and chemical properties between Al and Cu, the traditional fusion welding process is prone to produce welding defects such as oxidation, coarse grains, cracks, pores, and so on. However, the welding temperature of solid phase bonding technologies such as friction stir welding [7–9], linear friction welding [10], explosive welding [11], and cold rolling welding [12] is lower than the melting point of welding metal, which can help to avoid the above defects of fusion welding.

Continuous drive friction welding (CDFW), as one of the solid-state joining techniques, has significant advantages over the above-mentioned methods in the welding of bars, pipes, and other rotationally symmetrical workpieces [13]. During the CDFW process, the base material (BM) on one side is driven by torsional force to rotate at a certain rotation speed while the BM on the other side is driven by axial force to approach along the axial direction. The frictional heat generated by the contact between the end surfaces of the two BM bars causes the rapid softening of the materials. The metal on both sides is metallurgically...
bonded by the forging force and forms a welded joint. In general, the quality of the welded joints can be evaluated roughly by the morphology of the welds. Thus, some researchers have studied the formation and control methods of flashes morphology to obtain high quality welded joints. Sahin et al. [14], Meshram et al. [15], and Sathiya et al. [16] reported that opportune rotation speed, friction pressure, and friction time are the prerequisites for the formation of flashes, while the forging pressure and time are the factors that directly affect the shape and size of flashes. Luo et al. [17] found that the movement direction of flashes can be controlled by changing the structural shape of the end surface of welding bars. Meanwhile, optimizing several process parameters by controlling the friction torque in the CDFW can largely limit the amount of flutter in tubular welded joints. On the other hand, in the CDFW process, Al and Cu elements diffuse each other at the welding interface, which will react to form a certain number of intermetallic compounds (IMCs) that seriously affect the quality of the welded joints [15]. In consideration of this, Wei et al. [18] established a model to predict the type and rate of IMCs formation used by the effective Gibbs free energy change and found that Al$_2$Cu and Al$_4$Cu$_9$ are always present in all welded joints. Guo et al. [19] proved that there must be Al$_2$Cu, AlCu, and Al$_4$Cu$_9$ at the bonding interface in the temperature range of 400–500 °C using the effective heat generation model and determined their formation sequence. Additionally, some scholars have found that solid solution compounds can enhance the ultimate tensile strength (UTS) of the welded joints, while IMCs have the opposite effect [15]. Hence, in order to improve the UTS, researchers have modulated the morphology of the IMCs via various methods. On the one hand, some studies have reported on the regulation of the morphology of the IMCs layer in different parts of the joints by means of post-weld heat treatment [20,21]. Lee et al. [22], through annealing 1050 Al/Cu joints by the CDFW, found a sharp decrease in the electrical conductivity and mechanical properties of the joints as the thickness of the Al$_2$Cu and AlCu layers increased with increasing annealing time and temperature. On the other hand, the high-strength, efficient joints can also be obtained by pre-weld heat treatment to regulate the morphology of the IMCs layer [20].

Many process parameters, including rotation speed, friction time, friction pressure, forging time, and forging pressure, will affect the flashes and interface morphology, which determines the mechanical properties of the joint. Kimura et al. [23,24] studied the effect of friction pressure, friction time, and forging pressure on the UTS of A5052 Al/pure Cu joints using the CDFW. They found that higher strength-efficient joints can be obtained when using a lower friction pressure, a higher forging pressure, and a proper friction time. Li et al. [25] used AA1100 Al as an interlayer to study the effect of friction pressure and friction time on the UTS and interface microstructure evolution of Al/Cu joints. They reported that with an increase in friction time and friction pressure, the UTS increased at first and then decreased. However, it has been reported that the changes in friction pressure, friction time, forging pressure, and forging time had little effect on the interface morphology of Al/Cu joints [26]. There is evidently no unified understanding of the effect of process parameters on the morphology and properties of the dissimilar joints of Al and Cu by the CDFW. Therefore, it is essential to carry out more research on this topic.

The previous literature rarely reports the effect of rotation speed on the morphology and performance of the dissimilar Al and Cu joints by the CDFW, even though this parameter is vital. Researchers have used 6061-T6 Al in a wide range of engineering applications due to its excellent properties and affordability. Although there has been much research involving the welding of this material, research on its dissimilar welding with copper is relatively rare and far from supporting its industrial application. Consequently, with constant friction time, friction pressure, forging time, and forging pressure, the surface temperature, macroscopic morphology, microstructure, and mechanical properties of the 6061-T6 Al alloy and T2 copper joints obtained with six different rotation speeds for the CDFW were investigated in detail. The results of this paper can provide guidance for the engineering application of dissimilar metal joints by the CDFW of aluminum alloys and copper.
2. Materials and Methods

2.1. Materials

Commercially 6061-T6 Al and copper bars of 100 mm in length and 18 mm in diameter were selected as the BMs for the CDWF. The chemical compositions of both BMs are shown in Table 1, and the mechanical properties of both BMs are shown in Table 2. It can be seen that the UTS of the two BMs have similar values, and the yield strength (YS) of 6061-T6 Al is significantly larger than that of copper, while the elongation (El) of 6061-T6 Al is much smaller than that of copper.

Table 1. Chemical compositions of 6061-T6 Al and T2 copper (wt.%).

<table>
<thead>
<tr>
<th></th>
<th>Al</th>
<th>Mg</th>
<th>Si</th>
<th>Fe</th>
<th>Zn</th>
<th>Cu</th>
<th>Mn</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061-T6 Al</td>
<td>Bal.</td>
<td>1.0</td>
<td>0.6</td>
<td>0.6</td>
<td>0.25</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Copper</td>
<td>Bal.</td>
<td>0.005</td>
<td>0.005</td>
<td>0.001</td>
<td>0.002</td>
<td>0.005</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2. Mechanical properties of 6061-T6 Al and T2 copper.

<table>
<thead>
<tr>
<th>Materials</th>
<th>YS$_{0.2}$/MPa</th>
<th>UTS/MPa</th>
<th>El/%</th>
<th>Hardness/HV</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061-T6 Al</td>
<td>246 ± 6</td>
<td>290 ± 3</td>
<td>10.7 ± 1</td>
<td>95 ± 3</td>
</tr>
<tr>
<td>T2 copper</td>
<td>70 ± 1</td>
<td>295 ± 5</td>
<td>45 ± 3</td>
<td>105 ± 2</td>
</tr>
</tbody>
</table>

The metallographic specimens of the two BMs were obtained in the same way as the welded joints described subsequently. The optical microstructures and grain size distributions of the BMs are shown in Figure 1. The metallographic structure of 6061-T6 Al shows relatively coarse oval grains accompanied by a small number of fine grains, as shown in Figure 1a. Meanwhile, the metallographic structure of copper shows fine equiaxed grains with irregular polygons, as shown in Figure 1c. More than 500 grains were measured using Nano Measurer software according to the equivalent circle diameter of the grains, and the statistical results are shown in Figure 1b,d. The grain size of 6061-T6 Al presents a uniform distribution with an average grain size of 83.89 ± 10 µm, and the grain size of copper displays a gradient distribution with an average grain size of 15.54 ± 3 µm.

Figure 1. Optical microscopy images and grain size distribution of the BMs: (a) optical microscopy image, (b) grain size distribution of 6061-T6 Al; (c) optical microscopy image, (d) grain size distribution of copper. ($d_{ave}$: average grain size).
2.2. Experiment Methods

The welding experiments were carried out on a CDFW machine with a maximum power of 22 kW (C-20E-QJ, Changchun CNC Machine Tool limited company, Changchun, China). Before welding, the end surfaces of the BMs bars were polished using silicon carbide sandpaper and were then cleaned with anhydrous ethanol to remove impurities such as oil and dirt. Keeping the other process parameters constant, the rotation speed was set as a single variable and taken at equal intervals within the range of 700 rpm to 1200 rpm, as shown in Table 3. The whole welding process includes clamping the specimen, touching the end surfaces of the BMs bars, the friction stage, and the forging stage, as shown in Figure 2. During the welding process, the copper bar was held on the rotating side of the spindle to rotate at a set speed, and the 6061-T6 Al bar was placed on the moving side to move forward along the axial direction, as shown in Figure 2a. The surface temperature was measured using an industrial infrared thermometer (Fluke Ti400, Fluke, Everett, WA, USA), and the BMs bars’ surfaces were treated with black paint to reduce the reflection of infrared light.

Table 3. Process parameters selected for the welding experiment.

<table>
<thead>
<tr>
<th>Welding Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary friction pressure/MPa</td>
<td>1.2</td>
</tr>
<tr>
<td>Secondary friction pressure/MPa</td>
<td>1.5</td>
</tr>
<tr>
<td>Forging pressure/MPa</td>
<td>2.2</td>
</tr>
<tr>
<td>First friction time/s</td>
<td>9</td>
</tr>
<tr>
<td>Secondary friction time/s</td>
<td>6</td>
</tr>
<tr>
<td>Forging time/s</td>
<td>3</td>
</tr>
<tr>
<td>Rotation speed/rpm</td>
<td>700–1200</td>
</tr>
</tbody>
</table>

Figure 2. Welding process in the CDFW: (a) clamping the specimen; (b) end surface of bars touching; (c) friction stage; (d) forging stage.

The welded joints were cut along the radial–axial plane as the metallographic samples. The metallographic observation surfaces were ground using sandpaper and then polished with a gold velvet polishing cloth and a silica polishing solution. Metal on the copper side was etched in a solution containing 30 mL distilled water and 15 mL nitric acid for 60 s, while metal on the 6061-T6 Al side was etched in a solution containing 100 mL distilled water, 1 mL ammonia, and 2 g sodium hydroxide for 10 min. The metallographic structures of the samples were observed by optical microscopy (OM, OLYMPUS DSX500, Olympus, Japan), and the IMCs at the bonding interface were observed and analyzed using a scanning electron microscope.
electron microscope (SEM, JSM-IT500A, Jeol, Japan) equipped with an energy dispersive X-ray spectroscopy module (EDS, Oxford, England). The Vickers hardness tester (HVS-1000A, Huayin, China) was used to examine the microhardness of the joints along the direction perpendicular to the welding interface with a load of 200 g for 15 s, and the distance between the adjacent test points was 0.5 mm. The dimensions and a picture of the tensile specimens are shown in Figure 3. The weld was located in the center of the tensile specimen. The tensile test at room temperature was performed on a universal testing machine (Instron-5869, Instron, Norwood, MA, USA) with a constant strain rate of $1 \times 10^{-3}$ s$^{-1}$. This test was repeated three times to obtain representative results. The fracture surfaces of the tensile specimens were observed by SEM, and the element distributions on the fracture surfaces were analyzed by EDS to understand the metallurgical mechanisms of the welded joints.

![Figure 3. Dimension and picture of the tensile test specimens.](image)

### 3. Results and Discussion

#### 3.1. Surface Temperature and Macrostructure

Figure 4 shows the measured temperature of welded joints during the CDFW process under different rotation speeds. It can be seen that the copper side (left side) has a higher temperature than the 6061 Al side (right side), as is shown in Figure 4a. The reason for this phenomenon is that the thermal conductivity of Cu (390 W/m °C) is significantly larger than that of 6061 Al (167 W/m °C), and the frictional heat at the bonding surface as a heat source was transferred to the copper side faster, so this side exhibits a higher surface temperature. The trend of the surface peak temperature of the welded joints with the rotation speed is shown in Figure 4b. The surface peak temperature increased from 337 °C to 474 °C with an increase in the rotation speed in the range of 700 rpm to 1200 rpm. In fact, the temperature inside the welded joint is often greater than the measured temperature value of the joint surface. This trend of peak temperature variation with rotational speed has been previously reported [18]. This is attributed to the fact that the greater the rotation speed, the greater the linear relative velocity that occurred on the end surfaces of the BMs, resulting in more heat generation and greater surface peak temperatures.

The macro-morphology of welded joints obtained by different process parameters are displayed in Figure 5. All welded joints have a remarkable flash, which is significantly larger on the 6061 Al side than on the copper side. This is due to the deformation resistance of 6061 Al at a high temperature being obviously lower than that of copper, and the plastic metal of the softened 6061 Al side flows radially toward the outer edge of the bar under the action of the axial extrusion force [15]. In addition, with an increase in rotation speed, the flash volume of the 6061 Al side gradually increased. Meanwhile, there was also a slight deformation whereby the inner layer metal tends to open outward on the copper side. The specific process of this phenomenon was as follows: first, an increase in the rotation speed caused an increase in frictional heat at the joint surface; then, the frictional heat was transferred from the bonding surface to the BMs, and more thermal radiation resulted in...
more metal on both sides to reach a thermoplastic state, so that more plastic metal flowed to the outer edge of the bar in the form of flash under the action of the extrusion force.

Figure 4. Measured temperature results of welded joints: (a) surface temperature field; (b) surface peak temperature at different rotation speeds.

Figure 5. Macroscopic morphology of welded joints at a series of rotation speeds.

During the CDFW process, the frictional heat generated by the relative motion of the end surfaces of the two bars inevitably led to a certain temperature gradient when heat transfer was carried out on both sides. In other words, the temperature gradually decreased from the weld surface to the BMs located at the far side, which caused different microstructure morphologies along the axis of the welded joint. According to the grain shape and size, the welded joint can be divided into several distinct zones, as shown in Figure 6a. In particular, the 6061 Al side can be divided into three main zones: the dynamic recrystallization zone (DRZ), the thermomechanical affected zone (TMAZ), and the heat
affected zone (HAZ) [21,27]. The copper side has similar characteristics to the 6061 Al side and is not shown here as there are no clear boundaries between the zones. The widths of the zones on the 6061 Al side of the welded joints obtained by different rotation speeds at the R/2 position were measured. Since the width is variable along the radial direction, the measured width at the R/2 position was used as a representative, and the results are shown in Figure 6b. It is evident that with an increase in rotation speed, the width of each zone increased visibly, especially for TMAZ. During the CDFW process, the metal on both sides of the welding interface is simultaneously subjected to the combined actions of thermal radiation, axial force, and torque. In this case, the grains were deformed or coarsened, and the higher temperature induced microstructural changes in the BMs further away, so that they exhibit an increase in the width of each partition.

![Figure 6. Macrostructure subdivision of welded joints: (a) OM images of the welded joints; (b) the width of each zone of the 6061 Al side at different rotation speeds.](image)

3.2. Microstructure

Typical optical microstructures in each zone of the welded joints are illustrated in Figure 7. The DRZ closest to the bonding surface was subjected to the combined action of the grinding force perpendicular to the axial direction and the forging force parallel to the axial direction, where the original grains were broken, and then the broken grains experienced adequate dynamic recrystallization (DRX) due to the high temperature and plastic deformation. The grain morphology in the DRZ on the 6061 Al side can be described as fine equiaxed grains that are uniformly distributed, as shown in Figure 7d, while the DRZ on the copper side shows an inhomogeneous microstructure formed by fine equiaxed grains accompanied by a few coarse grains, as shown in Figure 7a. This suggests that the combined effect of frictional heat and force makes it easier for the 6061 Al side to undergo sufficient DRX, while inadequate DRX occurs on the copper side due to the limitations of its physical properties. The TMAZ experienced relatively low thermal radiation compared to the DRZ, which was not sufficient to cause adequate DRX; however, it can result in the accumulation of dislocations and the migration of grain boundaries, leading to grain deformation. Accordingly, the microstructure within the TMAZ on both the aluminum and copper sides exhibit elongated grains with their long axis perpendicular to the axial direction of the bar, as shown in Figure 7e,b. This indicates that the grains were deformed by axial extrusion with the action of thermal radiation. The microstructures of HAZ have similar characteristics to those of the BMs, with slightly coarser grains, as shown in Figure 7f,c. The temperatures at these zones can neither cause dynamic recrystallization
nor significant plastic deformation, and only lead to a slight coarsening of the grains due to grain boundary migration.

![Micrographs of welded joints](image)

**Figure 7.** Optical micrographs of the welded joints: (a) DRZ, (b) TMAZ, and (c) HAZ on the copper side; (d) DRZ, (e) TMAZ, and (f) HAZ on the 6061 Al side.

In order to discuss the effect of rotation speed on the microstructure of each region in detail, the main observation and analysis work was focused on the DRZ of the Al side. The metallographic micrograph in the DRZ of all welded joints shows fine equiaxed grains, which reveals that the grains experienced sufficient DRX during the welding process, as shown in Figure 8. The grain size distribution in the DRZ obtained by various rotation speeds was measured. The dataset was obtained by randomly counting over 500 grains using Nano Measurer software according to the equivalent circle diameter of the grains. With an increase in rotation speed, the grain size first decreased from 10.17 ± 3 µm at 700 rpm to 4.78 ± 1.2 µm at 1000 rpm, and then increased to 8.12 ± 0.6 µm at 1200 rpm, which is much lower than that of the 6061 Al grain size (60.66 µm). Within a certain range, the increase in rotational speed led to an increase in grinding force, which caused the grains to experience severe plastic deformation and to be broken rapidly. When the rotation speed exceeded this range, the temperature of the welded joint was significantly higher than that necessary for DRX of 6061 Al, and the recrystallized grains experienced significant growth behavior, resulting in an increase in the final grain size.

During the welding process, under the radiation of frictional heat, the softened weld metal was driven by torsional force and extrusion force, leading to the occurrence of plastic deformation and flow. At the same time, different elements on both sides of the bonding surface also produced mutual diffusion and mechanical mixing, thus forming a variety of IMCs. To understand the extent of elemental inter-diffusion, EDS line scans were performed at the bonding surfaces of welded joints, as shown in Figure 9. The results show that the thickness of the element diffusion layer increased from 2.44 µm to 7.22 µm when increasing the rotation speed from 700 to 1200 rpm. Elemental diffusion led to a change in the content of Al and Cu elements in the diffusion layer, which had a significant effect on the generation and evolution of IMCs and was closely related to temperature. As the rotation speed increases, the diffusion of elements at the bonding surface can be divided into three stages. First, when the rotation speed was 700 and 800 rpm, the maximum surface temperature at these processes was less than 360 °C according to Section 3.1 and the elemental diffusion layer was narrow, which is the stage where IMCs start to form and
the amount of IMCs is low. When the rotation speed was low, the lack of heat input led to a large difference in the softening of dissimilar metals and the low activity of the elements, making it difficult to produce extensive elemental inter-diffusion at the interface. Second, when the rotation speed was 900, 1000, and 1100 rpm, the maximum surface temperature was roughly in the range of 360 to 432 °C, and the elements were active, so there is a significant elemental diffusion gradient at the bonding surface, as shown in Figure 9c–e. Third, when the rotation speed was 1200 rpm, the highest surface temperature was 474 °C. The elements were extremely active, which drove the rapid growth of IMCs and resulted in a wider elemental diffusion layer, as shown in Figure 9f. Thus, it can be seen that with an increase in rotational speed and the higher temperature, the elemental diffusion layer widened, which may have contributed to the generation and development of IMCs.

Figure 8. Optical micrographs and grain size distributions of DRZ of the 6061 Al side of the welded joints at different rotation speed: (a) 700 rpm; (b) 800 rpm; (c) 900 rpm; (d) 1000 rpm; (e) 1100 rpm; (f) 1200 rpm.
when the rotation speed was 900, 1000, and 1100 rpm, the maximum surface temperature was roughly in the range of 360 to 432 °C, and the elements were active, so there is a significant elemental diffusion gradient at the bonding surface, as shown in Figure 9c–e. Third, when the rotation speed was 1200 rpm, the highest surface temperature was 474 °C. The elements were extremely active, which drove the rapid growth of IMCs and resulted in a wider elemental diffusion layer, as shown in Figure 9f. Thus, it can be seen that with an increase in rotational speed and the higher temperature, the elemental diffusion layer widened, which may have contributed to the generation and development of IMCs.

Figure 9. Elemental diffusion at bonding surface of the welded joints obtained by EDS line scanning at different rotation speeds: (a) 700 rpm; (b) 800 rpm; (c) 900 rpm; (d) 1000 rpm; (e) 1100 rpm; (f) 1200 rpm.

It has been reported that the higher the temperature of the CDFW welded joint, the more types of IMCs are generated [19]. The IMCs of Al–Cu welded joints were investigated in detail by Wei et al. [18]. They identified Al$_2$Cu and Al$_4$Cu$_9$ as the two major IMCs within all welded joints, while the third phase was probably CuAl. Pan et al. [27] found the same IMCs in welded joints of AA1060 aluminum alloy and copper based on compositional analysis. Therefore, in order to qualitatively analyze the IMCs in the joints of 6061-T6 Al and copper, EDS spot scanning was performed from the aluminum side to the copper side at the bonding surface of the welded joint with 1200 rpm to count the elemental content ratio of Al and Cu, as shown in Figure 10. The specific Al and Cu element content ratios are shown in Table 4. Based on the elemental content ratios in the table, it can be inferred that the IMCs likely include Al$_2$Cu, AlCu, and Al$_4$Cu$_9$.

Table 4. Composition of the selected test points marked in Figure 10.

<table>
<thead>
<tr>
<th>Position</th>
<th>Al</th>
<th>Cu</th>
<th>Al/Cu</th>
<th>Possible Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDS spot1</td>
<td>93.33</td>
<td>6.67</td>
<td>13.99</td>
<td>Al</td>
</tr>
<tr>
<td>EDS spot2</td>
<td>66.74</td>
<td>32.26</td>
<td>2.10</td>
<td>Al$_2$Cu</td>
</tr>
<tr>
<td>EDS spot3</td>
<td>49.79</td>
<td>50.21</td>
<td>0.99</td>
<td>AlCu</td>
</tr>
<tr>
<td>EDS spot4</td>
<td>35.50</td>
<td>64.50</td>
<td>0.55</td>
<td>Al$_4$Cu$_9$</td>
</tr>
<tr>
<td>EDS spot5</td>
<td>13.84</td>
<td>86.16</td>
<td>0.16</td>
<td>Cu</td>
</tr>
</tbody>
</table>
3.3. Mechanical Properties

3.3.1. Microhardness

The microhardness along the axial distribution at R/2 of the welded joints was measured, and the microhardness distribution curve of each welded joint is shown in Figure 11. All curves have similar distribution characteristics, showing a sharp peak at the bonding surface and a sudden decrease in hardness values towards both sides. As the rotation speed increased, the hardness value at the bonding surface increased from 120 HV to 157 HV, which is obviously higher than that of the two BMs. Ouyang et al. [28] pointed out that the hardness of IMCs is significantly higher than those of 6061 Al and copper. This indicates that the hardness values at this location are dominated by IMCs. Similar findings have been reported in previous studies [3,28]. Xue et al. [3] reported that the hardness value at the weld center was much higher than that in the other zones under the strengthening effect of three kinds of IMCs (Al$_2$Cu, AlCu, and Al$_4$Cu$_9$). In addition, for all welded joints, there is a slight softening zone on the Cu side and a significant softening zone on the Al side. The appearance of this softening zone has been reported in previous studies [29,30]. On the Cu side, this is due to the thermal effect, which causes the original copper with a work-hardened state to form a corresponding thermal softening zone [27]. In this case, the Cu metal undergoes a recovery or recrystallization process that causes the disappearance of various dislocation structures [31]. On the Al side, the 6061-T6 Al experienced a combination of severe heat radiation and axial force during the welding process, and some strengthening precipitates dissolved into the aluminum matrix, which resulted in
the softening of the metal [30]. The microhardness profiles also show that the softening zone became more significant with increasing rotational speed, which was caused by more thermal radiation. This phenomenon corresponds with the widening trend of each zone with increasing rotation speed as can be seen in Figure 6. According to the microstructure morphology of each zone in Figure 7, the grains on both sides of the bonding surface were significantly refined, thus indicating that the Hall–Petch relationship is not the dominant factor in the hardness variation. As a result, the microhardness distribution of welded joints in different regions was dominated by different factors.

![Microhardness distribution curves of the welded joints at different rotation speeds](Image)

**Figure 11.** Microhardness distribution curves of the welded joints at different rotation speeds (copper is left, 6061Al is right).

In summary, a high hardness at the bonding surface was affected by the IMCs, with a slight softening on the Cu side due to thermal effects and a significant softening on the Al side due to the dissolution of the strengthening phases. This hardness distribution phenomenon is more significant at increased rotational speeds.

### 3.3.2. Tensile Properties

Uniaxial tensile tests of welded joints at room temperature were performed, and the results with typical representations in each set of tensile specimens are plotted as stress–strain curves in Figure 12a. The mechanical properties of the six welded joints corresponding to the curves are shown in Figure 12b. The UTS of the welded joints increased at first and then decreased with an increase in the rotation speed. In particular, the UTS of the joint with a rotation speed of 1000 rpm was the largest (212 MPa), reaching 73.1% of the strength of the 6061 Al BM (290 MPa). All welded joints failed at the bonding surface, and the elongation of all joints was less than 2.5% with a brittle fracture characteristic. Pan et al. [27] and Li et al. [21] reported that when the thickness was within a certain range, the IMCs were not the main factor affecting the UTS of the joint. However, due to the large differences in the coefficients of linear expansion between 6061 Al and copper, the IMCs can induce cracking. When the rotation speed was low (700 or 800 rpm), the insufficient heat input resulted in poor metallurgical bonding and thin IMCs, so that the tensile properties of welded joints were comparatively poor. When the rotation speed was high (1200 rpm), the excessive heat input could not only give rise to a larger grain size but also thick IMCs, as shown in Figures 8f and 9f. During the tensile test, the brittle hard IMCs can easily cause micro-cracks, resulting in a low UTS. Therefore, the IMCs are a key factor affecting the tensile strength of welded joints.
The fracture morphology and element distribution on the copper side at different rotation speeds were observed by SEM to reveal the mechanisms and the type of fracture exhibited by the specimens during tensile testing, as shown in Figure 13. When the rotation speed was 700 rpm or 800 rpm, the dominant feature of the fracture surface is plentiful cleavage surfaces filled with numerous small flat facets and tear ridges, and a small amount of Al elements were distributed in a net-like pattern on the copper matrix, as shown in Figure 13a,b. When the rotation speed was 900 rpm or 1000 rpm, the tensile fracture morphology was mainly composed of large dimples covered with the increasing Al element and a few cleavage surfaces filled with a small amount of Cu element, while the tearing ridges were more pronounced, as shown in Figure 13c,d. When the rotation speed was at 1100 or 1200 rpm, the second phase particles containing Mg and Si elements dissolved, and the Al and Cu elements exhibited a diffuse cross-over distribution, which was consistent with the wider elemental diffusion layer shown in Figure 9e,f. However, the fracture morphology of these welded joints exhibited a broad flush plane, which was caused by the brittle IMCs, as shown in Figure 13e,f. As a result, although all welded joints were characterized by brittle fractures at the macroscopic level, the fracture type of the welded joints shows only slight differences at different rotational speeds, which is influenced by the metallurgical bonding and IMCs due to the distribution of elements.
Figure 13. SEM images showing fracture surfaces and elements at the copper side of welded joints at different rotation speeds: (a) 700 rpm; (b) 800 rpm; (c) 900 rpm; (d) 1000 rpm; (e) 1100 rpm; (f) 1200 rpm.

4. Conclusions

In this paper, dissimilar CDFW was performed on 6061-T6 Al and copper bars, and the effect of different rotation speeds on the surface peak temperature, macrostructure, microstructure, and mechanical properties of welded joints were investigated. The following conclusions can be drawn:

1. An increase in the rotation speed can lead to an increase in the temperature, which makes the flash and welded zone of the joints larger.
2. The microstructure of 6061-T6 Al exhibited fine equiaxed grains in the DRZ, deformed elongated grains in the TMAZ, and slightly coarsened grains in the HAZ.
3. With an increase in the rotation speed, the average grain size in the DRZ on the Al side first decreased and then increased, and the elements’ inter-diffusion at the bonding surface was gradually significant, which was attributed to the combined effect of force and heat.
4. The microhardness on the bonding surface was significantly greater than that of the BMs due to the presence of IMCs, and there was a softening zone on both sides of the bonding surface. This inhomogeneity of hardness distribution gradually became more obvious as the rotation speed increased.
5. When the rotation speed was 1000 rpm, the UTS exhibited its greatest value of 212 MPa, while the joining efficiency was 73.1% of the strength of 6061-T6 Al base material. The failure of all welded joints occurred at the center of the weld, and the fracture surfaces exhibited brittle fracture features.

Author Contributions: Conceptualization, X.Z. and L.X.; methodology, Y.F.; validation, X.X.; investigation, P.W.; resources, X.Z. and C.J.; writing—original draft preparation, X.Z. and L.X.; writing—review and editing, X.Z.; project administration, S.Y. and C.J. All authors have read and agreed to the published version of the manuscript.

Funding: This study was financially supported by the Jilin Province Development and Reform Commission (2021C038-4), the Science and Technology Development Projects of Jilin Province (20210204143YY), the Scientific research project of Jilin Provincial Department of education in 2021 (JJKH20211078KJ), the Science and Technology Development Projects of Changchun (21ZY25), the Graduate Innovation Fund of Jilin University (101832020CX116), and the Chongqing Research Institute of Jilin University (CQRIJLU2021CY-GG018).
Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data presented in this study are available on request from the corresponding author. Data are not publicly available due to ongoing, concurrent efforts in this subject.

Conflicts of Interest: The authors declare no conflict of interest.

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