Effect of the rotational speed of on the surface quality of 6061 Al-alloy welded joint using friction stir welding

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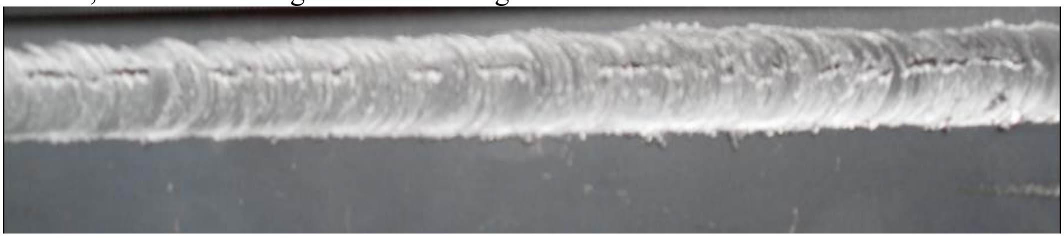
Abstract. The rotational speed of the stir-welding head is an important technological parameter in friction stir welding (FSW) process. For investigating the effect of the rotational speed of the stir-welding head on the surface quality of the welded joint, in this study, the weld tests were conducted under different rotational speeds (in which the welding speed was fixed), and then the effects were analyzed using the heat-fluid analysis model established. The test results revealed that cracks or grooves could be observed on the welded joint at small rotational speeds; with the increase of rotational speed, the weld surface became bright and clean; as the rotational speed further increased, the surface of the welded joint may be over burnt. Through analysis, it can be observed that appropriate increasing the rotational speed of the stir-welding joint increased the heat input in welding; meanwhile, fewer materials participated in the formation of weld, the material's flowability was improved, and the resistance that impeded the advance of the stir-welding needle was reduced, thereby improving the quality of the welded joint.

1. Introduction

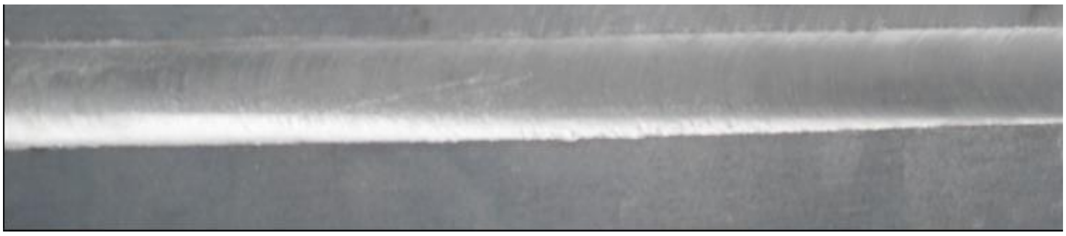
Friction stir welding (FSW) is a novel solid-state bonding technology and shows many advantages compared with the traditional welding methods. FSW can weld many metals that were hardly welded in the past [1-6]. However, when using FSW, an unreasonable setting of some technological parameters would lead to poor-quality welded joint and further affect its practical use. A high-speed rotation of the stir-welding head is the guarantee for the success implementation of FSW since it is tightly correlated with the heat input during welding. It is still unclear whether the quality of the welded joint can be improved by enhancing the rotational speed of the stir-welding joint. This paper conducted FSW weld tests at different rotational speeds and established the heat-fluid model for exploring the reason why the variation of rotational speed of the stir-welding head can affect the quality of welded joint.

2. Technological test of FSW

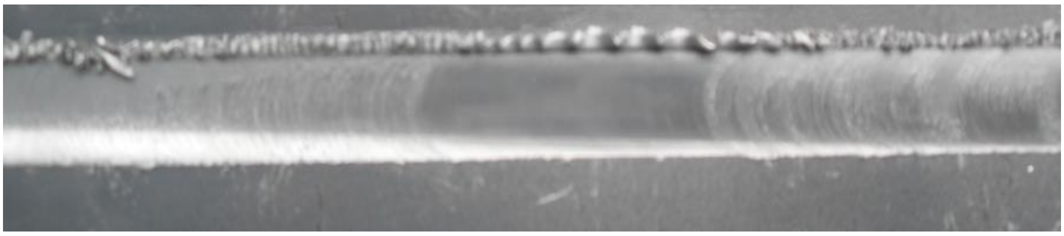
6061 aluminum (Al) alloy plates with a size of 150 mm×50 mm×6.3 mm were used in the present test. The weld tests were conducted under different conditions, i.e., the rotational speed of the stir-welding head was set at 450 r/min, 650 r/min and 850 r/min, respectively, during which the welding speed was fixed as 60 mm/min. Figure 1 shows the appearance of the welds. As shown in Figure 1(a), at a rotational speed of 450 r/min, the poor-quality weld was formed, accompanied by irregular surface and many grooves; at a rotational speed of 650 r/min, favorable weld with a smooth surface can be observed in Figure 1(b); at a rotational speed of 850 r/min, as shown in Figure 1(c), rough selvedge was produced, and over burning-induced blurring can also be found on the weld surface.



（a）ω=450 r/min



（b）ω=650 r/min



（c）ω=850 r/min

Figure 1. Effect of different rotating speed on joint quality.

3. Establishment of heat-flux analysis model

During traditional welding process, heat input is related to the applied welding current and voltage. By contrast, FSW is a kind of machining methods and shows no direction connection with the welding specifications. To analyze the rotational speed of the stir-welding head on the quality of the welded joint, this study established the heat-flux analysis model based on fluid dynamics theory. According to this model, the material was regarded as the laminar, viscous and non-Newtonian fluid that flowed around the cylinder [7], and heat-fluid coupling condition at quasi-stable state was then analyzed by solving the fluid's continuity equation, momentum equation and energy equation.

The heat input in welding is sourced from the friction heat in the contact region between the stir-welding head and the workpiece as well as the plastic-deformation-induced heat. At the quasi-stable state, the friction shearing stress at any a point in the contact region equals to the shearing stress during the occurrence of plastic deformation [7]. In this study, the deformation heat produced in the processing was also taken into account.

The heat produced by the friction between the shaft shoulder and the workpiece in the contact region as well as the plastic deformation can be written as:

$$q_{zj} = C_f \left(\frac{\pi n R}{30} - U \sin\theta\right)\tau_{yield} \tag{1}$$

The heat produced by the friction between the side of the stir-welding needle and the workpiece in the contact region as well as the plastic deformation can be written as:

$$q_{zc} = C_f (\frac{\pi n r}{30} - U \sin\theta)\tau_{yield} \tag{2}$$

The heat produced by the friction between the bottom of the stir-welding needle and the workpiece in the contact region as well as the plastic deformation can be written as same as Equation (1).

In Equation (1) and Equation (2), Cf denotes the ratio of the heat produced in the contact region between the stir-welding head and the workpiece to the heat transferred to the workpiece and was set as 0.85 in this study (i.e., = 0.85); n denotes the stir-welding head's rotational speed; U denotes the workpiece's movement speed (which was equal to the welding speed but in an opposite direction); R denotes the distance between any a point in the contact region between the shaft shoulder and the workpiece and the rotational axis of the stir-welding head; r denotes the radius of the stir-welding needle; θ denotes the angle between the line connecting any a point in the contact region between the shaft shoulder and the workpiece and the rotational axis and the workpiece's movement direction; τ_{yield} denotes the shearing stress when the material is yielded. The relation between yield strength and shearing stress can be expressed as:

$$\tau_{yield} = \sigma_s / \sqrt{3} \tag{3}$$

On the other hand, the material's yield strength decreases with rising temperature [5]. When the temperature increases to some value, the yield strength is reduced to 0 and no heat is produced in the contact region between the stir-welding head and the workpiece; then, the temperature stops increasing.

As stated above, this study adopted 6061 Al alloy for analysis. Al alloy has a melting point of 855 K, whose density shows slight variation with the temperature and approximately equals to 2700 kg/m3. Through fitting, the variations of heat conductivity coefficient, specific heat Cp and yield strength with temperature can be expressed as:

$$\lambda = 25.22 + 0.3978\mathrm{T} \tag{4}$$

$$C_p = 929.3 - 0.627T \tag{5}$$

$$\sigma_s = \begin{cases} 182.16 + 0.71544T - 0.00134T^2 (T \le 477K) \\ 3671.57 - 14.290T + 0.01870T^2 (T \le 855K) \end{cases} \tag{6}$$

In the calculation model, the stir-welding head rotated counterclockwise, and the workpiece moved along the positive direction of x-axis from left to right at a constant welding speed of 50 mm/min. To reduce the calculation time, only part of the workpiece was calculated. As shown in Figure 2, the cylindrical region, with a dimension of 52 mm× 6.3 mm× 50 mm, was taken into calculation. The x-axis length was twice of the diameter of shaft shoulder.

The shaft shoulder, the side and the bottom of the stir-welding needle were regarded as the heat-input boundaries, as the heat-flux formula described in Equation (1) and Equation (2). The upper and lower surfaces, as well as the advancing and backward sides of the stir-welding needle, were set as the moving walls, with a speed equivalent to the workpiece's movement speed. The fluid's inlet was set as the speed's inlet boundary condition, and the velocity equaled to the movement speed of the workpiece; its outlet boundary was set as the pressure's outlet boundary condition. The upper surface was exposed to the air and regarded as a heat-convection boundary, with a heat convection coefficient of 50 W/(m2•K); the lower surface was in contact with the base plate, with a heat conduction coefficient of 500 W/(m2•K); both the advancing and backward sides were partly in contact with the air and partly in contact with the fixture, and the heat conduction-convection coefficient was set as 200 W/(m2•K) while the temperature was set as 300 K.

The calculation region was then modeled using Gambit. Next, the model was meshed and then imported into Fluent (fluid dynamics software); the calculation was conducted using implicit, linear

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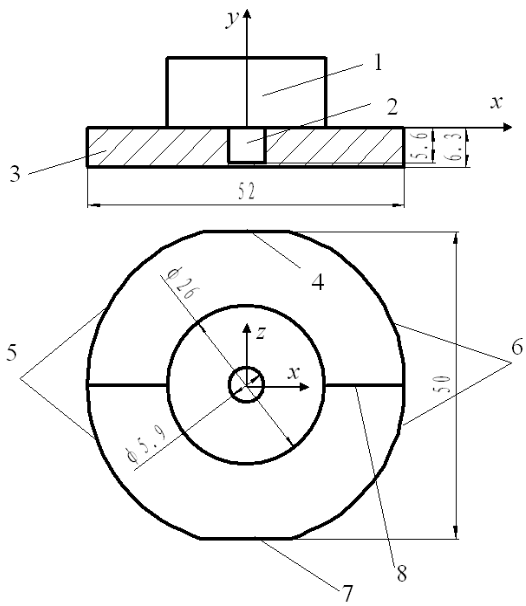
and separate resolver and the mesh was discredited. During the solving process, the pressure was calculated according to the standard discrete equation, the momentum equation was calculated using the second-order upwind equation, and the energy equation was calculated using the first-order upwind equation.



1 shaft shoulder 2 stir-welding needle 3 workpiece 4 forwarding side 5 inlets 6 outlets 7 retreating side

Figure 2. Schematic of computational zone.

4. Results and discussion

4.1. Effect of the rotational speed on peak temperature

Figure 3 showed the peak temperatures when the rotational speed of the stir-welding head was set as different values, during which the welding speed was set at 50 mm/min. It can be observed that, at a small rotational speed, the peak temperature increased significantly with the increase of rotational speed; as the rotational speed increased to 600r/min, the peak temperature almost reached a stable value. This is because that, when the welding speed and the size of the stir-welding head are fixed, the heat input in welding process is related to the rotational speed of the stir-welding head and the maximum shearing stress of the material. With the increase of the rotational speed, the material's temperature rose, while the material's maximum shearing stress remained unchanged due to temperature increment; therefore, peak temperature remained constant. Regarding energy consumption, the rotational speed of the stir-welding head should not exceed 600r/min. During FSW, the peak temperature is 80%~90% of the melting point [7]; accordingly, if only the heat quantity is taken into account, a rotational speed of 200r/min still can satisfy the welding requirements.

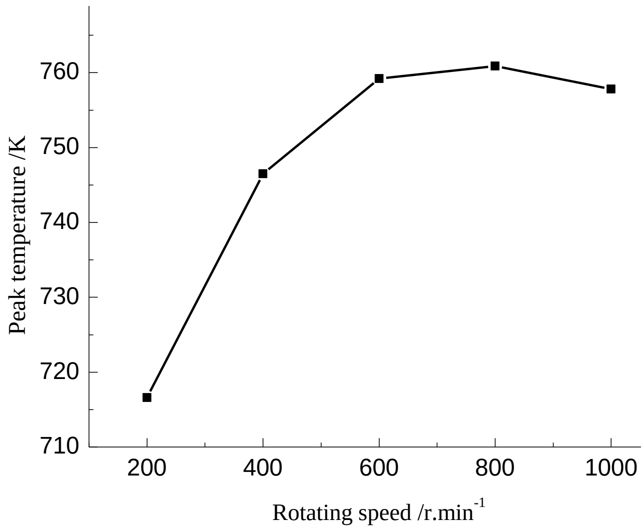


Figure 3. Effect of different rotating speed on peak temperature.

At a small rotational speed, less heat was input, and the material was poor in flowability; however, more materials should be welded from the front of the stir-welding needle, and the back of the stir-welding head and some were unable to migrate, thereby producing cracks or grooves. With the increase of the rotational speed of the stir-welding head, the heat-input increased, the material's flowability was significantly improved and fewer materials needed to be migrated, thereby enhancing the quality of the welded joint. As the rotational speed of the stir-welding head further increased, although heat input remained unchanged, fewer materials were migrated; accordingly, the heat was focused on few materials and resulted in over burning.

4.2. Effect of the rotational speed on longitudinal force

Figure 4 showed the longitudinal forces when the rotational speed of the stir-welding head was set at different values, during which the welding speed was also set at 50 mm/min. With the increase of the rotational speed, the longitudinal force further decreased, and the curve began to flatten. As the rotational speed increased, the heat input in welding increased continuously, the material's temperature and strain rate increased but the flow stress decreased, and the resistance that impeded the advance of the stir-welding head decreased; therefore, materials were more easily migrated from the front to the back of the stir-welding needle. However, when the rotational speed of the stir-welding head was increased to some value, the temperature was no longer changing, while the material's strain rate continued increasing, thereby slowing down the material's flow stress. From the perspective of the tool's service life, the rotational speed should be increased, but it may lead to poor-quality welded joints and increase energy consumption.

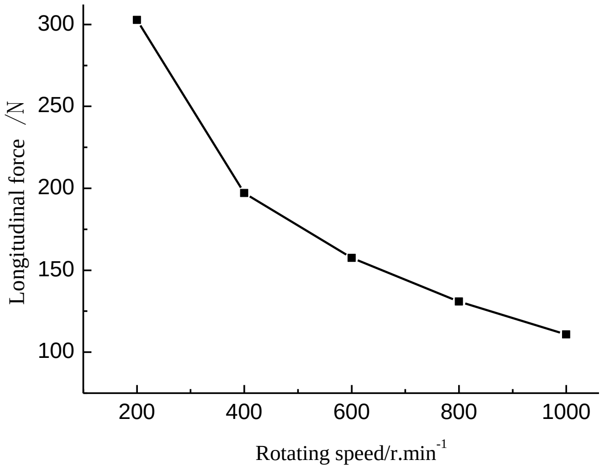


Figure 4. Effect of different welding speed on longitudinal force.

5. Conclusions

Appropriately increasing the rotational speed of the stir-welding head improved the surface quality of the welded joint; however, at a higher rotational speed, the poor quality welded joint was produced. The increasing of the rotational speed of the stir-welding head would lead to produce more heat input; therefore, fewer materials participated in the formation of the weld, the material's flowability was improved, and the forward resistance decreased. The setting of the rotational speed of the stir-welding head should take overall consideration. Both the quality of the welded joint and the tool's service life should be balanced.

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