THE EFFECT OF TOOL GEOMETRY ON MATERIAL FLOW BEHAVIOR OF FRICTION STIR WELDING OF TITANIUM ALLOY

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Abstract:

Based on the RNG k-ε model, the finite volume model of friction stir welding of Ti6Al4V alloy is established by ANSYS FLUENT software. The effect of rotational tool geometry on titanium alloy flow behaviour is exhibited. The results of numerical simulation show that the flow direction of material near the rotational tool is the same as that of the rotational direction of the rotational tools.. The flow velocity of material near the rotational tool is much bigger than that of other regions in a weldment while the peak value appears near the shoulder edge. Changing either the rotational tool shoulder diameter or the pin tip diameter, the flow direction of material during the welding process will always remain unchanged. With an increase of the shoulder and pin tip diameter, the material flow velocity increases. However, from the point of view of elimination of root defects, increasing the diameter of the pin tip is better than increasing the diameter of the shoulder.

1 Introduction

Titanium alloy is widely used in the field of aerospace because it offers many advantages, such as high specific strength, good tenacity and perfect corrosion resistance, etc. Therefore, it is necessary to develop the joining technology of titanium alloy. As a kind of a new solid-state joining method, friction stir welding (FSW) offers the characteristics of high joint quality and non-pollution [1,2], which makes FSW become the researching hotspot of titanium alloy [3-6].

Similar to the microstructure and the mechanical properties of the FSW joint [7], material flow behavior in FSW is one of the most important researching fields [8], which influences the quality of FSW joints very much. However, it is difficult for the experimental method to attain the material flow during FSW of titanium alloy, which results in high costs of the rotational tool, high machining costs of titanium alloys and the small weldable thickness of titanium alloys. Therefore, many experimental methods suitable for FSW of aluminum alloy, which include the steel ball tracing technology, the stop-action technology and the

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marker material method, are not used to research the material flow of FSW of titanium alloy [9,10]. In comparison with FSW of aluminum alloy, FSW of titanium alloys still in the state of exploration and the numerical simulation of plastic flow behavior of material during the welding process of titanium alloy is reported to be less researched [11-13]. Zhao et al. [11] employed commercial Computational Fluid Dynamics software FLUENT and researched the material flow behavior of titanium alloy on the basis of a laminar flow model, in which the relationship between the viscosity of titanium alloy, the temperature and the strain rate was not considered.

In this study, the finite volume model of FSW of Ti6Al4V has been established and then the material flow behavior during the welding process researched with FLUENT software. The effects of variation of the shoulder diameter and the pin diameter on material flow velocity have been demonstrated. The results shown in the paper are good for the optimization of welding procedure and the optimization of rotational tool geometry.

2 Finite volume model of FSW

2.1 Control equations

During the process of FSW, the material near the rotational tool is in the state of superplasticity in order to mix enough and get a high quality joint. So material can be considered to be fluid and then a turbulent flow model is used in the finite volume model of FSW of titanium alloy. In order to simplify the numerical simulation process, some supposed conditions are fulfilled: (1) the rotational tool is perpendicular to the surface of a weldment; (2) The solid non-slip condition is used in the finite volume model to describe the relation between the rotational tool and the metal material contacting with the tool; (3) The material is considered to be incompressible fluid, whose viscosity is isotropic; (4) the temperature used in the model is 1273K , i.e. in the stable-state condition [14].

In the numerical simulation process of 3D flow field of FSW joint, the material flow in FSW joint mainly follows the equation of mass conservation, the momentum conservation equation and the energy conservation equation.

In the FSW process, the mass of material is supposed to be a constant, so the equation of mass conservation is as follows:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0\,, \tag{1}$$

where u, v and w mean the velocity of x direction, y direction and z direction, respectively.

The momentum conservation equation can be described with the Navier-Stokes equation. The expression of the equation is as follows:

$$\begin{cases}\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=Fx-\frac{1}{\rho}\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)\\ \frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=Fy-\frac{1}{\rho}\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)\\ \frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=Fz-\frac{1}{\rho}\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)\end{cases} \tag{2}$$

where Fx, Fy and Fy are the volume force of x direction, y direction and z direction, respectively; p is the static pressure of the flow field; μ is the viscosity of fluid; ρ means the mass of material.

The energy conservation equation can be expressed as follows:

$$\rho c\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}\right)=\lambda\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \tag{3}$$

where c is the specific heat of material, λ is the thermal conductivity of material and T is the temperature of fluid.

2.2 Mesh generation of model

GAMBIT is pre-processing software of FLUENT, which is used to establish a model of the rotational tool. In this study, the rotational tool is made up of the rotational pin with a cone shape and the shoulder with a plane surface, as shown in Fig. 1.

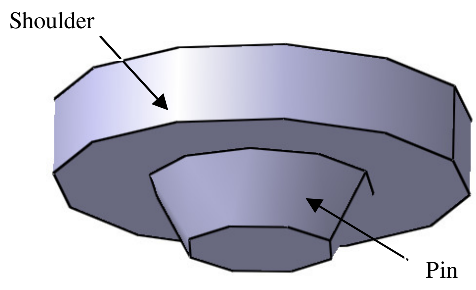


Figure 1. A solid model of a rotational tool used in friction stir welding.

The diameter of the pin root is 6 mm, the diameter of the pin bottom is 4 mm, the length of the rotational pin is 1.8 mm and the diameter of the shoulder is 11 mm. Moreover, the dimension of the weldment is 150 mm × 50 mm × 2.5 mm. The mesh generation of the model is shown as Fig. 2.

2.3 Boundary condition

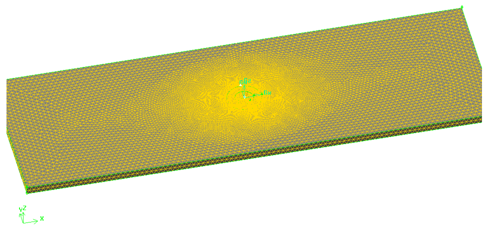
The surface of a weldment, the bottom of a weldment, the advancing side, the retreating side, the fluid inlet and the fluid outlet are all supposed to be part of the moving wall while the speed of the moving wall is equal to the welding speed and the moving direction is opposite to the welding direction. In the numerical simulation, the welding speed is 60 mm/min. Moreover, the elements, which are used to represent both the shoulder and the pin, are supposed to be the rotational wall while the rotational velocity and the rotational direction of wall are both the same as those of the rotational tool. In the numerical simulation, the rotational velocity is 800 r/min and the rotational direction is clockwise. Moreover, the temperature of 1273 K is added to the inlet, the outlet and all the walls of the model.

2.4 Material parameters

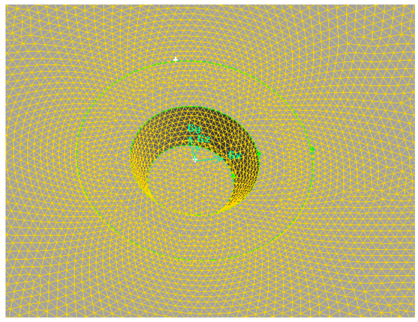
In the numerical simulation of FSW of titanium alloy, the RNG k-ε model is used. The material parameters of the melting metal of Ti6Al4V used in this study are mainly the specific heat, the thermal conductivity, the coefficient of viscosity and the mass, whose values are 879 J/Kg·K, 15.91 W/m·K, 5.3 mPa·s and 4.45 g/cm3, respectively [11].

3 Results and discussion

In order to research the material flow field during FSW, several sections are analyzed, as shown in Fig. 3. Therein, the section *a*, section *b* and section *c* are all parallel to the weldment surface while the minimum distance of the section *a*, section *b* and section *c* away from the shoulder of the rotational tool are 0.1 mm, 0.9 mm and 2.2 mm, respectively. In other words, the section *a*is close to the surface of the weldment, the section *b* is in the middle of the weldment and the section *c* is between the rotational pin tip and the bottom of the weldment. Also, the section *d* is analyzed, which is perpendicular to the welding direction and the rotational axis of the tool.



(a) 3D model



(b) Partial enlarged figure

Figure 2. Mesh generation of model.

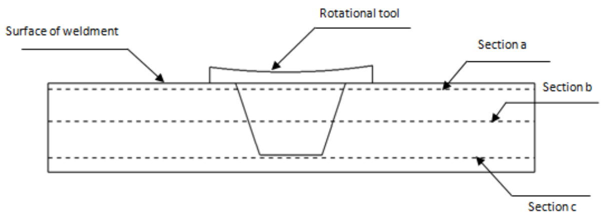


Figure 3. Positions of different sections of the weldment.

3.1 Results of 3D flow field

Fig. 4 shows the 3D distribution of the flow field during the welding process of titanium alloy, which is attained by using the rotational tool in Fig. 1. Fig. 5 presents the material flow velocity field of the section *d*. In order to easily analyze, the velocity along x direction is omitted in Fig. 5. Fig. 6 depicts the material flow velocity vector of different sections parallel to the weldment surface.

The figures show that the flow direction of material near the rotational tool is mainly clockwise, which is the same as the rotational direction of the rotational tool. The material near the rotational tool flows violently, where the flow velocity is much higher than that in other regions inside the weldment.

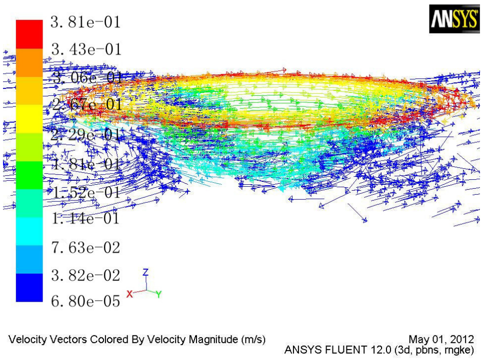


Figure 4. 3D Flow field during the welding process of titanium alloy.

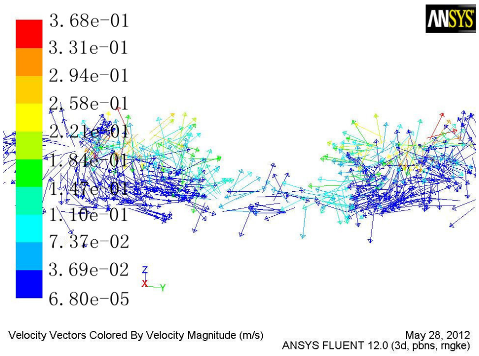
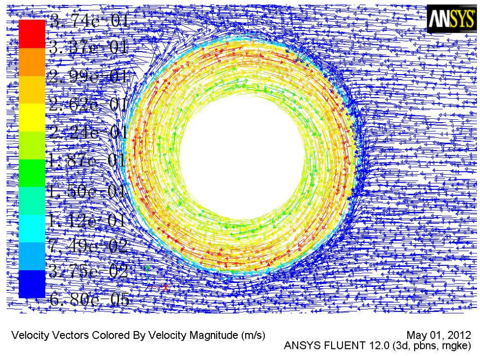
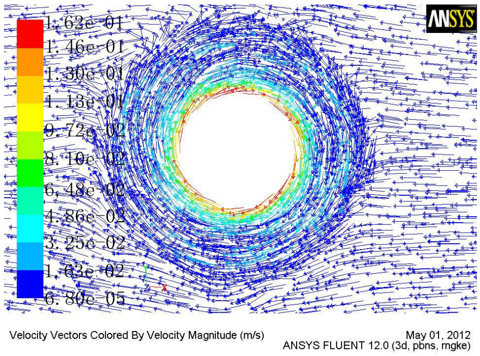


Figure 5. Flow velocity field of the section d of titanium alloy during the friction stir welding process.

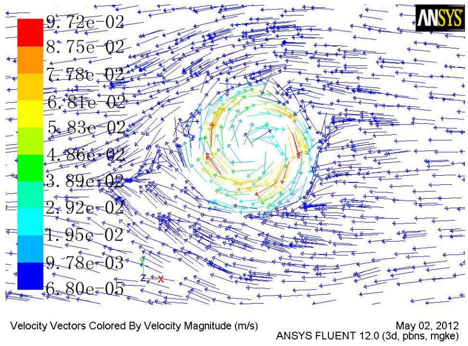
For the material in the direction perpendicular to the weldment surface, due to the change of the rotational pin diameter, the flow velocity decreases and the region under the high flow velocity decreases with an increase in distance away from the weldment surface. Because of the influence of the shoulder, the material in section *a* flows violently while the value of flow velocity changes from 0.114 m/s to 0.374 m/s. Considering the material in the section *b*, the region of high flow velocity value is relatively big due to the influence of the rotational pin while the value changes from 0.00816 m/s to 0.162 m/s. The material in the section *c* doesn't flow enough and the root defect easily appears. Moreover, the peak value of the material during the welding process appears in the region which is the contact zone between the edge of the shoulder and the surface of the weldment.



(a) Section a



(b) Section b



(c) Section c

Figure 6. Flow velocity field of material in different parallel sections.

3.2 The effect of the shoulder diameter on material flow

In order to research the shoulder diameter effect on material flow behavior, a rotational tool is designed, whose diameter is 14 mm while the geometry of the rotational pin is the same as the tool shown in Fig. 1.

Fig. 7 shows the flow velocity field of the section *d* with the shoulder diameter of 14 mm. Fig. 8 depicts the flow velocity vector of the section *a,* section *b* and section *c*.

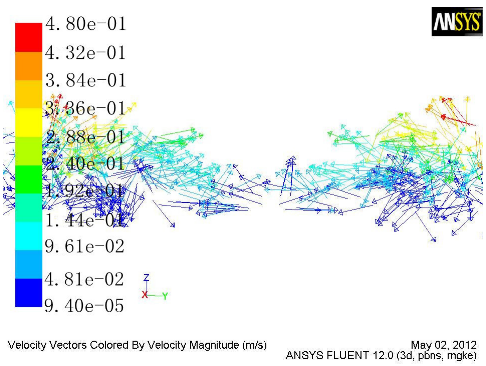
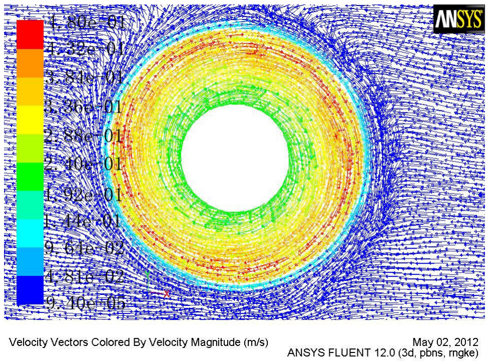
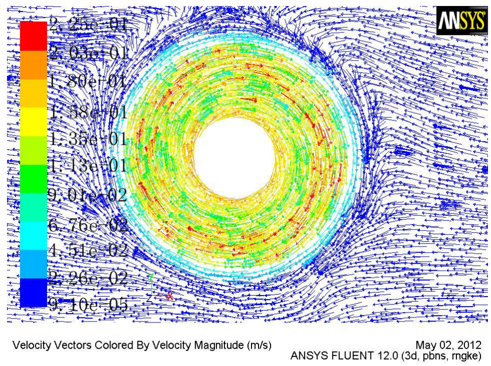


Figure 7. Flow velocity field of the section d of titanium alloy during the friction stir welding process.

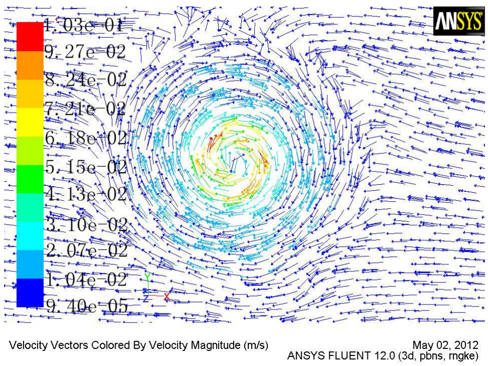
Integrating data from Fig. 5 and Fig. 6, it is evident that the change in the shoulder diameter has no influence on the flow direction of material during friction stir welding of titanium alloy. During the welding process, if we increase the diameter of the shoulder, (if the diameter of the shoulder is increased,) we also increase the flow velocity of material near the weldment surface very much,(the flow of velocity of material is also increased very much), which results in the increase of flow velocity inside the welded material and consequently, this exerts an influence on the quality of FSW joint. In fact, increasing the shoulder diameter makes the temperature of welding joint increase. To any welding methods, the welding temperature is one of the key factors that influences the quality of welding very much. Providing that other welding conditions are unchanged, an increase in the welding temperature can make welding residual stress and welding residual distortion increase, which makes the quality of the welding joint worse[15]. Therefore, although increasing of the shoulder diameter is good for material flow behavior, the shoulder diameter must be chosen reasonably according to the actual situation.



(a) Section a



(b) Section b

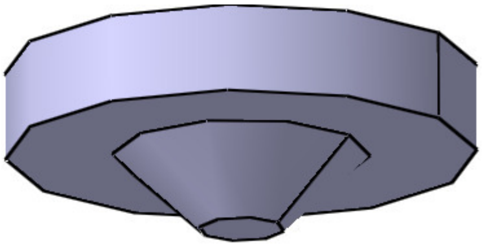


(c) Section c

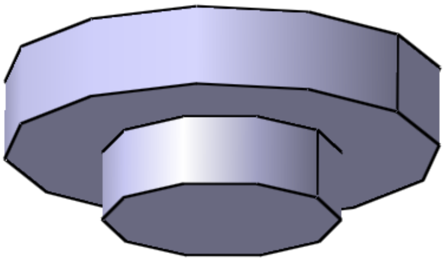
Figure 8. Flow velocity field of material in different sections.

3.3 The effect of the pin tip diameter on material flow

In order to research the effect of the pin geometry on material flow behavior, two kinds of rotational tools are designed, as shown in Fig. 9. Therein, the rotational tool shoulder diameter and the pin root diameter are both equal to that in Fig. 1, while the diameters of the pin tip in Fig. 9a and Fig. 9b are 2 mm and 6 mm, respectively.

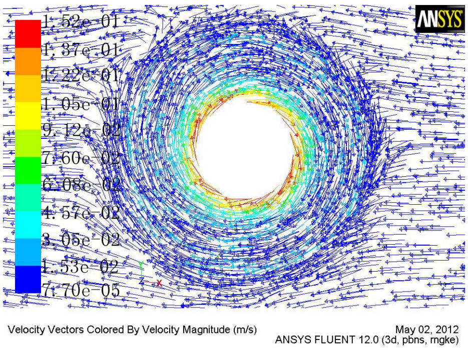


(a) 2mm

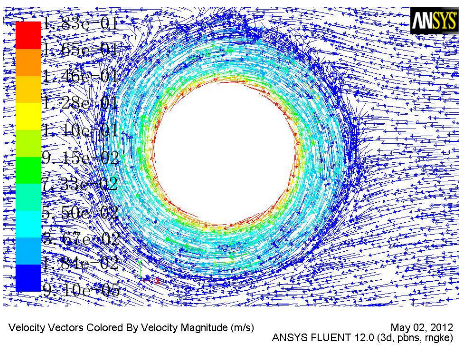


(b) 6mm

Figure 9. A solid model of a rotational tool with different r pin tip diameters.



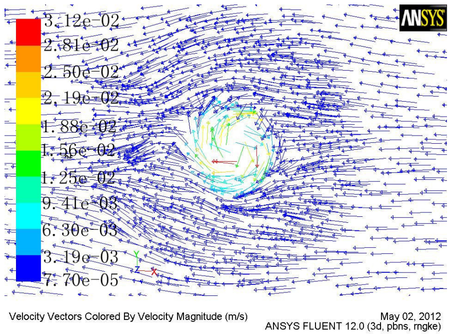
(a) 2mm



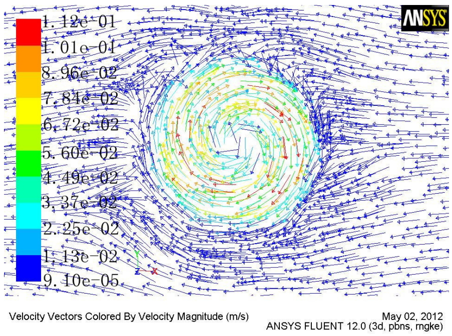
(b) 6mm

Figure 10. Flow velocity field of the section b under the different pin tip diameters.

Fig. 10 and Fig. 11 represent the flow velocity field figures of different sections attained by the two rotational tools in Fig. 9. Integrating data with Fig. 6, it is evident that the change of the pin tip diameter can greatly influence the flow velocity of material while the flow direction of material remains unchanged. With an increase of the pin tip diameter, the flow velocity of material inside the weldment increases, which is good for the quality of welding joints. In fact, with an increase of the rotational pin diameter, the heat input during the welding process increases [16], which is similar to the increase of the shoulder diameter. Moreover, in the welding process of titanium alloy, the force between the shoulder and weldment is big, which requires big rigidity of the rotational tool. Therefore, in the process of choosing the reasonable rotational pin diameter, the flow velocity, the welding temperature, the rigidity of the rotational tool must be simultaneously discussed.



(a) 2mm



(b) 6mm

Figure 11. Flow velocity field of the section c under different f pin tip diameters.

4 Conclusion

(1) During the process of friction stir welding of Ti6Al4V alloy, the flow direction of material near the rotational tool is the same as the rotational direction of the rotational tool. The region of high flow velocity appears near the rotational tool while

the region of the peak value is on the rotational shoulder edge.

(2) If both the shoulder diameter and rotational pin diameter increase, the flow velocity of material will also increase Moreover, an increase of the shoulder diameter can improve the flow velocity of material near the weldment surface while an increase of the pin tip diameter can be good for the material inside the weldment.

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