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Numerical Simulation Method of Roller Hemming on Variable Curvature Aluminium Alloy Sheet with Adhesive

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Abstract. To realize the roller forming process of curved edges of aluminium alloy auto-body closure panels, a numerical simulation method is proposed for the roller forming of aluminium alloy sheet with adhesive in flat variable curvature. Firstly, the motion of the roller is calculated by the discrete variable curvature curve method. Secondly, a numerical method of FEM-SPH coupling is established to simulate the interaction between the adhesive layer and the sheet. Subsequently, a numerical simulation model for the roller forming of aluminium alloy sheet with adhesive in flat variable curvature was constructed and finite element calculations were carried out. The simulation results show that the motion posture of the roller matches that of the actual roller, and the adhesive layer can adequately fill the inner and outer panel areas during the rolling process, which proves the effectiveness of the method.

Keywords. Roller-hemming forming, Variable curvature aluminium alloy sheet, Adhesive, SPH-FEM coupled.

1. Introduction

Roller hemming is increasingly being used in the manufacture of autobody closure panels. Firstly, the inner side of the outer panel is coated with hemming adhesive. Secondly, outer panel is bent by the roller driven by the industrial robot, while the adhesive flows during the rolling process, and the outer panel produces plastic deformation to wrap the inner board, thus realizing the wrap of the inner and outer panel.

With the development of automotive lightweight technology, aluminum alloy materials are more and more widely used in auto-body. Due to the poor ductility and formability of aluminum alloy, it is easy to break and crack in the bending area of the outer panel, and it is easy to wrinkle, warp, indent and swell on the surface of the plate. These defects greatly affect the surface forming quality. In addition, the physical and chemical properties of the adhesive and metal materials are very different. During the roller-hemming process, the adhesive flows and creates a heterogeneous coupling effect with the metal sheet. These make it difficult to study the roller-hemming mechanism and forming quality of aluminum alloy sheet with adhesive.

The profile of the automobile closures is complex, and the curve shapes are more

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common. For the purpose of analysis, the roller hemming can be divided into four categories according to the curve profile: flat surface-straight edge hemming, flat surface-curved edge hemming, curved surface-straight edge hemming, and curved surface-curved edge hemming [1]. The door structure and edge type are shown in figure 1. It is easy to realize the flat straight-edge roller hemming on the robot, but for curved surface or curved-edge rolling, the rolling system becomes complex. It is difficult to realize the motion of the roller along the curve and to control the posture of the roller at each time.

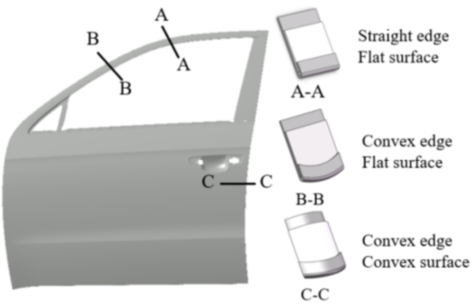


Figure 1. The structure of roller hemming.

Thuillier,S [2] et al. investigates the process of roller hemming on thin aluminum-magnesium alloy sheets with a flat single curvature curved edge and compares the geometry of the roll-formed sheet with that of a conventionally hemmed sheet. The results show that the indentation values of the rolled edges are much lower than those of conventional cladding for the same material and sheet dimensions. The rolling process of plane straight edge is studied by Hu, X [3]. The results show that roller hemming can be regarded as a kind of plane strain bending deformation process, and the bending part is easy to break and the flanging part is easy to produce waves. Gürgen [4] et al. studied the process of roller forming of flat single curvature curved edge aluminum alloys. The influence of the rolling angle, the plate thickness and the roller diameter on the forming quality is investigated. However, the variable curvature of the plane is not considered in the paper, and the influence of the adhesive on the forming process is neglected. Limon-Leyva [5] et al. studied the roller forming process with linear and non-linear trajectories on two oblique planes and optimized the geometric parameters such as roller radius, pre-hemming angle and fillet height.

Li [6] et al. studied the pressure-viscosity effect in a planar straight-plate model. The roller hemming process of AA6106-T4 aluminum alloy sheet was simulated by fluid-solid coupling method. The results show that with the increase of adhesive layer thickness, the rolled-in value of aluminum alloy panel increases. To sum up, the main research direction of the roller hemming is in the plane straight edge or the plane single curvature curved edge rolling at present. However, the study of plane variable curvature curved sheet is still insufficient. The rolling mechanism of aluminum alloy sheet with adhesive is less studied. Relevant models need to be developed.

In this paper, the process of roller hemming on a variable curvature aluminum alloy sheet with adhesive, AA6016-T4, is investigated. Firstly, the posture of the roller is calculated by means of the discrete variable curvature curve method. Next, a numerical model of the FEM-SPH coupling was developed to effectively simulate the interaction between the adhesive and the thin panel. Numerical simulations are carried out by setting the boundary conditions of the roller's motion posture. By studying the process of roller hemming on variable curvature aluminum alloys, the basis is laid for improving the quality of the forming. In addition, the motion of the joints of the robot can be solved inverse from the motion posture of the rollers. The method provides support for the robot to perform flat curved edge roller hemming.

2. Theoretical Analysis

2.1. The Method of Discrete Variable Curvature Curve

In the roller hemming process, the axis of the roller is always perpendicular to the tangent direction of the curve to ensure a higher quality of the roller hemming. In addition, the roller rotates around its axis under the action of friction. Assuming that the curve is defined on the X-Y plane, the motion of the roller is superimposed by the following motion patterns: (1) The roller moves horizontally along the X axis. (2) The roller moves horizontally along the Y axis. (3) The roller rotates around the Z axis. (4) The roller rotates around its axis. The motion of the roller is defined by the method of discrete variable curvature curve. The curves are transformed into connected multi-segment straight lines to achieve the purpose of curvilinear roller hemming.

Firstly, set the starting motion time t_s and the ending time t_e of the roller, Divide the running time of the roller by *h*. Where in the *i* moment

$$t_i = t_s + \frac{1}{h}\left(t_e - t_s\right)\left(i-1\right), i = 1\cdots h+1 \tag{1}$$

Secondly, the trajectory of the rollers is divided into *h* equal parts according to equal chord lengths. The position P_i of the point of the roller in the coordinate system is obtained. Corresponding P_i and t_i to prepare the boundary conditions for the simulation.

Then, solve for the vector between two neighboring points V_j in turn. The vector V_j is the movement of the rollers in the X and Y axis.

$$V_j = P_{i+1} - P_i, j = 1\cdots h \tag{2}$$

Then, calculate the angle θ_i between two neighboring vectors in turn. θ_i is the rotation of the rollers around the Z axis.

$$\theta_k = \arccos\left(\frac{V_{i+1} \bullet V_i}{\|V_{i+1}\|\|V_i\|}\right), k = 1\cdots h-1 \tag{3}$$

The use of rigid beam units coupled to the rollers enables the rollers to rotate around their axis. The method for discrete curves of variable curvature is shown in figure 2 where the dotted lines indicate the axis of the rollers.

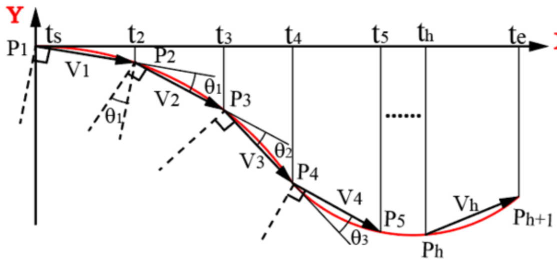


Figure 2. The method of discrete variable curvature curve.

2.2. FEM-SPH Method

The FEM and SPH algorithms are two important approaches to computational mechanics. The FEM is a grid-based Lagrange algorithm that allows better analysis of the sheet forming process, while the SPH is a particle-based Lagrange algorithm whose computational accuracy is not affected by the degree of material deformation and is suitable for solving problems with large deformations and high strain rates, and is widely used in fluid simulation. The fundamental principle of SPH is to describe continuous fluids by discretizing them into interacting particles. Each individual particle carries physical quantities such as mass and velocity associated with itself. By solving the kinetic equations for the set of masses and tracking the motion of each mass, the final state of motion of the entire fluid is obtained. The SPH equation is established by kernel function interpolation and particle approximation.

The specific formula for the particle approximation is as follows [7]:

$$f(x)=\sum_{j=1}^{N}\frac{m_j}{\rho_j}f(x_j)W(x-x_j,h) \tag{4}$$

Where m_j and ρ_j is the mass and density of the particle j, respectively. N is the total number of particles within the influence area of the particle at x. $W_{i,j}=(x-x_j,h)$ is Kernel function.

3. Numerical Simulation of Roller Hemming on Aluminum Alloy Sheet with Adhesive

3.1. Model Parameters

This paper carries on the simulation based on Abaqus software. The rolling model is composed of inner panel, outer panel, roller, adhesive and holder, as shown in figure 3. Pre-hemming and final hemming were used in the study, with hemming angles of 45° and 90° respectively. The tapered roller is used for the pre-hemming and the cylindrical roller for the final hemming. The assembly relationship of the model is shown in figure 4. In the hemming, the point on the roller bus becomes the tool center point, and the point on the holder edge line is called the robot target point. Therefore, the distance between the roller bus and the holder edge line is called TCP-RTP. The parameters of the roller gemming model are shown in the table 1.

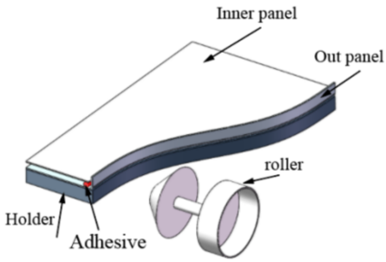


Figure 3. FEM-SPH model for roller forming.

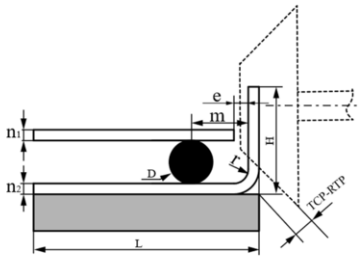


Figure 4. Assembly dimensions of the model.

Table 1. Main parameters of the roller hemming model.

Parameter names	Unit	Value
Inner and outer panel length *L*	mm	190.89
Outer panel thickness n_2	mm	1
Inner panel thickness n_1	mm	0.8
Distance between inner and outer panel *e*	mm	2
Flange height *H*	mm	10
Inner flange radius *r*	mm	1.8
Roller taper	°	45
Roller diameter	mm	70
Distance from the center of the adhesive to the outer panel	mm	4
Diameter of the adhesive *D*	mm	4
Pre-hemming TCP-RTP	mm	1.5
Final hemming TCP-RTP	mm	4.4

3.2. Material Parameters

Aluminum alloy sheet of AA6016T4, which is widely used in automobile exterior panels, is selected as the material for both the inner panel and outer panel. The material properties are shown in table 2. In the study, the common automotive commercial adhesive was selected as the hemming adhesive. The material properties at room temperature are shown in table 3.

Table 2. Properties of aluminum alloy sheet material.

Parameters	Unit	Value
Density ρ	Kg/m^3	2710
Young's modulus *E*	*MPa*	70000
Poisson's ratio μ	-	0.3
Yield strength	*MPa*	129
Tensile strength	*MPa*	242
Hardening index *n*	-	0.28

Table 3. Main characteristic parameters of hemming adhesive.

Parameters	Unit	Value
Density ρ	g/cm^3	1.25
Dynamic viscosity μ	$Pa \cdot s$	250
Solid containing rate	%	≥99
Elongation at break	%	4
Peel strength τ_p	*MPa*	≥30

3.3. Mesh Generation

The inner panel, outer panel and adhesive are set as deformable body, and the roller and holder are set as rigid body. In order to analyze the forming of aluminum alloy panel more accurately, the meshes of aluminum alloy inner panel and outer panel are defined as three-dimensional solid elements. The outer panel bending area and rolling area were divided into denser meshes to ensure better simulation quality. The mesh elements of adhesive are set to convert to particles.

3.4. Boundary Conditions

In practice, round-trip roller hemming is usually used to avoid the accumulation of rolling defects. In order to allow the adhesive between the inner panel and the outer panel flow fully and fill the gap between the inner and outer panels, Pitch between inner and outer panel is set as 0.3mm. Therefore, the inner panel is pressed down 3.7mm in the adhesive squeezing step at the beginning of roller hemming. The roller is then fed to the outer panel for pre-hemming. Then the roller is switched to a cylindrical roller for final hemming. As shown in the figure 5.

Based on the curve discretization method above, the motion posture of the roller at each time step is calculated, as shown in figure 5. And it is assigned to the load setting of the roller. The feed direction of the roller is shown in figure 6. During the simulation, a hinge connection unit was used in ABAQUS in order to allow the rollers to rotate around their axis.

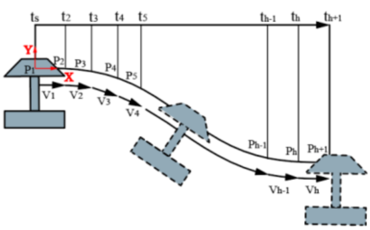


Figure 5. Motion posture of roller.

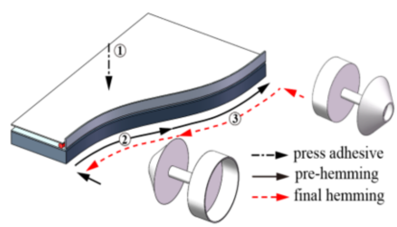
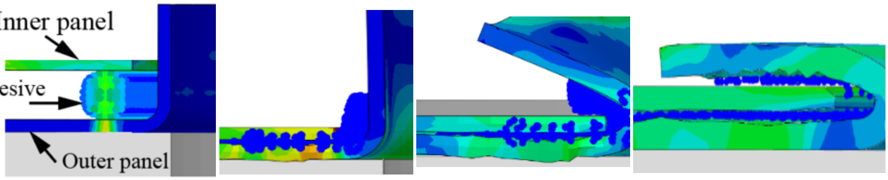


Figure 6. The feed direction of the roller.

4. Results

Figure 7 shows the entire flow of the adhesive during the roller hemming process. At the beginning of rolling, the hemming adhesive is transformed into SPH particles, as shown in the figure 7(a). As the process of goes on, the hemming adhesive is squeezed and flows, part of which flows between the inner and the outer panel, and the other part gradually fills the corner of the outer panel, as shown in the figure 7(b). In pre-hemming, the adhesive gradually flows to the upper side of the inner panel, as shown in the figure 7(c). In final hemming, the adhesive on the upper side of the inner panel is squeezed by the outer panel to fill the gap between the two panels. as shown in the figure 7(d).



(a) (b) (c) (d)

Figure 7. Flow state of adhesive in roller hemming process.

Figure 8 shows the motion posture of the roller at the end of pre-hemming. Figure 9 shows the motion posture of the roller at a certain moment in the final hemming. The axis of the roller is always perpendicular to the tangent of the outline of the outer panel.

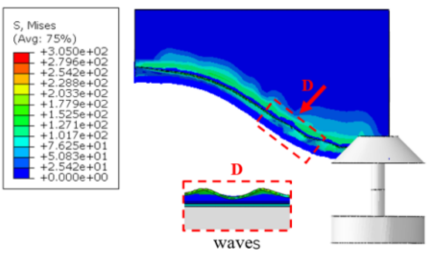


Figure 8. The motion posture of the roller at the end of the pre-hemming.

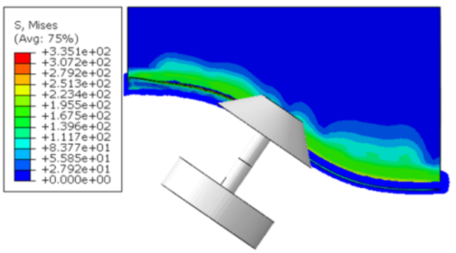


Figure 9. The motion posture of the roller at a given moment during the final hemming.

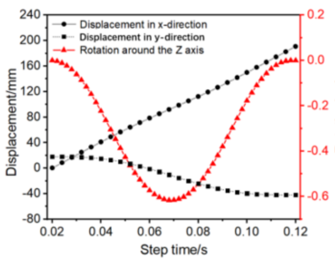


Figure 10. The motion posture of the roller in the whole pre-hemming process.

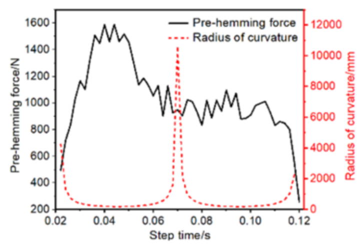


Figure 11. Reaction force of the roller and the changes of the radius of curvature in pre-hemming.

The motion posture of the roller in the whole pre-hemming process is shown in figure 10. The motion posture of the roller is consistent with the actual motion of the roller, which proves that the method of discrete variable curvature curves can effectively solve the hemming forming problem of aluminum alloy sheet with plane curved edge. Figure 11 shows the reaction force of the roller during the pre-hemming process and the changes of the radius of curvature. In the process of pre-hemming, the reaction force of the roller on the concave surface is larger than that on the convex surface.

5. Conclusions

In this paper, a method of discrete plane variable curvature curve is proposed. By this method, the motion posture of the roller is calculated and the roller hemming along the curve of variable curvature is realized. It effectively solves the difficulty of setting the motion posture of the roller in the process of hemming on plane curved edge. At the same time, the motion of each joint of the robot can be inversely solved by the motion posture of the roller, which provides the support for the robot to roll with planar curved edges.

The roller forming analysis model of aluminum alloy sheet with planar variable curvature was established, and the interaction between hemming adhesive and panel was simulated effectively by FEM-SPH coupling method. By extracting the reaction force of the roller, the relationship between the radius of curvature and the reaction force of the outer panel profile was analyzed, which laid a foundation for improving the hemming quality of variable curvature curve aluminum alloy panel.

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