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SIMULATION OF MICROSTRUCTURE EVOLUTION DURING EXTRUSION OF LARGE DEPTH-TO-DIAMETER RATIO VARIABLE CROSS-SECTION HOLLOW SHAFTS OF 6061 ALUMINUM ALLOY

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The hollow slender shaft is characterized by intricate component features such as a significant depth-to-diameter ratio, variable cross-sections, and non-uniform thin walls. Uneven deformation of the hollow slender shaft during deformation results in degradation of service performance. In this study, the deformation uniformity is explored from a microscopic point of view, the numerical simulation model of dynamic recrystallization of 6061 aluminum alloy is established with the DEFORM-3D software. And grain evolution during the aluminum alloy extrusion process was theoretically analyzed using the cellular automata.

Key words: 6061 aluminum alloy, hollow slender shaft, defrom software, dynamic recrystallization, cellular automata

INTRODUCTION

In recent years, rapid advancements have been observed in sectors like aerospace, automotive, and high-end equipment. Notably, high-performance hollow slender shafts with a significant depth-to-diameter ratio (L/D > 10) and variable cross-sections have emerged. These components, while maintaining their rigidity and fatigue life performance metrics, allow for significant material and weight reductions. They have been increasingly incorporated into new energy vehicle drive systems and high-performance motor spindles, reflecting promising application prospects and widespread market demand. However, manufacturing challenges are posed by these shafts due to their complex internal structures, high length-to-diameter ratios, thin walls, and stringent form and positional accuracy requirements. At present, the conventional deep hole drilling technique remains the dominant method for the internal machining of such parts, both domestically and internationally, although it is often associated with high wastage rates sub-optimal material utilization, and reduced processing efficiency.

DANA Company, based in Germany, has specialized in hollow shaft technologies. Through optimized cross-sectional designs, lightweight tubular shapes with maximized specific strength and rigidity are achieved. The dynamic performance and strength of the hollow shafts can be fine-tuned as a result. A segmented forging process is employed to form the hollow shaft with its variable cross-section and intricate internal structures. These segments are then joined using friction welding, enabling the creation of various internal and external shapes and splines. This technique has been adopted by various OEMs, enhancing driving performance and fuel economy, and is instrumental in the production of high-precision hybrid transmission input shafts and power steering shafts, particularly for electric and hybrid vehicles. The team led by Professor Zhang [1] from Xi’an Jiaotong University successfully fabricated large depth-to-diameter ratio, variable cross-section hollow slender shafts using rotary forging technology. This method is recognized for significantly enhancing processing efficiency and reducing production costs. Advantages of radial precision forging/rotary forging technology, such as superior surface processing accuracy, quality, and a high degree of automation, have been documented, particularly in the context of manufacturing components with stepped and non-standard hole structural features.

Extensive efforts have been devoted by the part rolling forming technology research team at Ningbo University [2] to the study of rolling forming theories and equipment technology. Specialization in the rolling forming of rotary parts has been achieved, enabling efficient, material-saving, energy-saving, and near-net-shape forming of components. The “axial piercing + oblique rolling” process has also been developed to produce hollow shaft components.

The approach of fabricating hollow slender shafts based on the “high-temperature extrusion feeding + high-temperature thinning deep drawing” composite forming principle remains scarcely researched, with industrialization not yet realized, marking it as an untouched niche within the industry. The composite hol-

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low shaft extrusion forming process in this paper exhibits attributes such as good malleability, high forming efficiency, elevated material utilization, reduced forming load requirements, and high form and positional accuracy of the formed parts. Suitability for mass production has been noted, potentially leading to precision machining processes for the internal holes of large depth-to-diameter ratio, variable cross-section hollow slender shafts. Potential applications for this research have been identified in strategic military domains, including submarines, aircraft, and armored vehicles, especially in the realm of manufacturing complex variable cross-section hollow slender shaft components with stepped internal holes.

MATERIALS AND METHODS

The raw material employed for extrusion is sourced from 6061 aluminum alloy rods. This alloy is a member of the Al-Mg-Si alloy series. Detailed chemical compositions of the material are tabulated in Table 1. A schematic representation of the finished part is depicted in Figure 1.

Table 1 **Parameters of 6061 aluminum alloy / wt.%**

Parameter	Value
Si (mass fraction)	0,40-0,80
Fe (mass fraction)	≤ 0,70
Cu (mass fraction)	0,15-0,40
Mn (mass fraction)	≤ 0,15
Mg (mass fraction)	0,80-1,20
Cr (mass fraction)	0,04-0,35
Zn (mass fraction)	≤ 0,25
Ti (mass fraction)	≤ 0,15
Al (mass fraction)	Bal

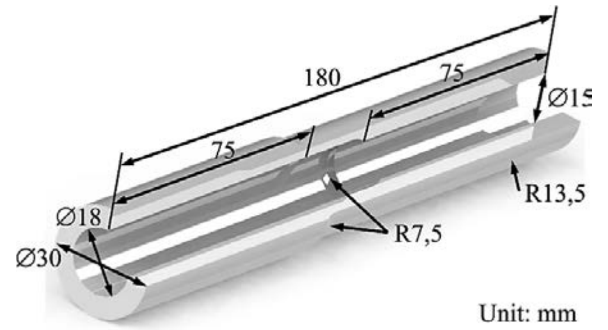

Figure 1 3/4 Extruded Hollow Shaft Workpiece Model

The finite element simulation was carried out by DEFORM-3D software. Due to the symmetric model, the 1/4 model (Figure 2) was used for the finite element simulation to ensure computational efficiency. The Φ 60 mm × 40 mm cylindrical billet was set as the plastic body, the number of relative units was divided into 40 000 and the volume compensation was turned on at the same time. The extrusion die parts were set as rigid bodies, the shear friction between the billet and the contact surface of the extrusion die parts was 0,3, and the heat transfer coefficient was 11 $Ns^{-1}mm^{-1}°C^{-1}$. The material of the billet is 6061 aluminum alloy, and the flow stress data and thermo-physical parameters were retrieved from the DEFORM material library. Set the extrusion speed to 10 mm/s and the billet temperature to 400 °C.

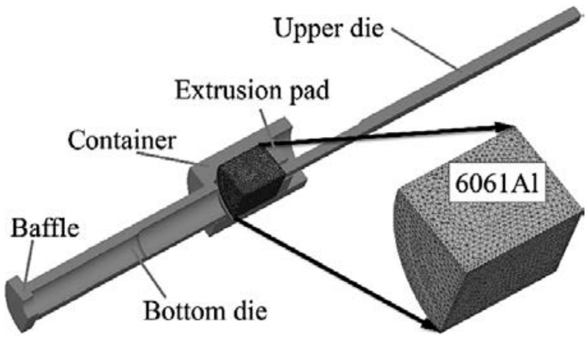

Figure 2 Simulation model

RESULTS AND DISCUSSION

Dynamic recrystallization

During the extrusion process, 6061 aluminum alloy undergoes work hardening, dynamic recovery (DRV), and dynamic recrystallization (DRX). The DRX degree during extrusion is one of the key factors in improving the comprehensive mechanical properties of the shaft. The DRX evolution during extrusion was adopted from the DRX model of 6061 aluminum alloy established by Zhang [3].

Critical strain of DRX:

$$\begin{cases} \varepsilon_p = 7,81\times10^{-4}\,\dot{\varepsilon}^{0,162}\exp\left(\dfrac{33\ 872}{RT}\right) \\ \varepsilon_c = 0,8\varepsilon_p \end{cases} \tag{1}$$

The kinetic model of DRX:

$$\begin{cases} X_{drex} = 1-\exp\left\{-1,0237\left[\dfrac{\varepsilon-\varepsilon_p}{\varepsilon_{0,5}}\right]^{1,2624}\right\} \\ \varepsilon_{0,5} = 1,5\times10^{-4}\,\dot{\varepsilon}^{0,0232}\exp\left(\dfrac{42\ 680}{RT}\right) \end{cases} \tag{2}$$

DRX grain size model:

$$d_{rex} = 119,28\varepsilon^{0,632}\dot{\varepsilon}^{-0,107}\exp\left[\dfrac{-16\ 540}{RT}\right] \tag{3}$$

where e_p is peak strain, e_c is critical strain, R is gas constant, T is temperature, $\dot{\varepsilon}$ is strain rate, X_{drex} is dynamic recrystallization volume fraction, $e_{0.5}$ is the strain of 50% DRX, and d_{rex} is the size of the average grain size for DRX.

Figure 4a-c show the DRX grain percentage evolution during the extrusion process. At the early stage of extrusion, the grain deformation at the inner wall reaches the critical strain (Figure 3a), and obvious dynamic recrystallization occurs. As the deformation continues, DRX also occurs at the outer wall (Figure 3b). After fur-

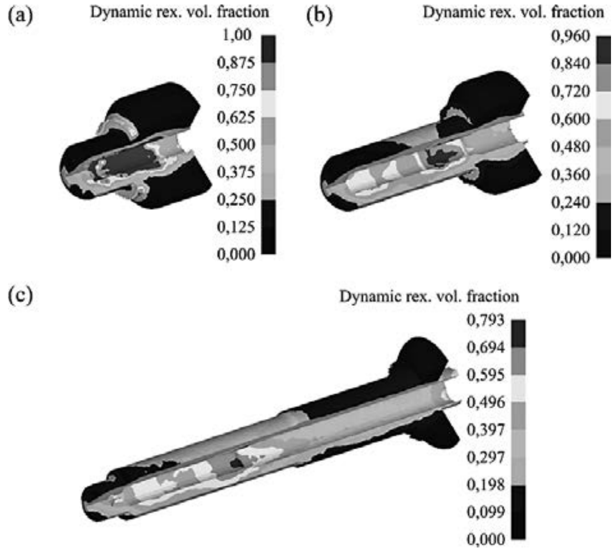

Figure 3 Dynamic recrystallization percentage evolution based on extrusion process

ther extrusion, the inner and outer wall grains started to undergo continuous nucleation growth (Figure 3c).

Cellular Automata (CA)

In the DEFORM-3D post-processing module MICROSTRUCTRE3, the area of the CA model is set to 250 × 250 with a length of 2 and a periodic boundary is used. The metameric neighborhood takes the Moore criterion and sets the neighborhood radius to 1.

Dislocation density evolution modeling using the Laasraoui-Jonas model [4].

$$\begin{cases} d\rho = (h - r\rho)\,d\varepsilon - \rho dV \\ h = h_0\left(\dfrac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{m} \exp\left(\dfrac{mQ}{RT}\right) \\ r = r_0\left(\dfrac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{-m} \exp\left(-\dfrac{mQ}{RT}\right) \\ N_r = \left[\dfrac{(\# Rows)\times(\# Columns)\sqrt{2}}{K}\right]^2 \\ \quad \times h(d\varepsilon)^{(1-2m)} \end{cases} \tag{4}$$

Where e is strain, ρ Dislocation density, *h* is the hardening coefficient, *r* is the dynamic recovery softening coefficient, h_0 is hardening constant, *m* is rate sensitivity, R is gas constant, T is temperature, *Q* is activation energy, *V* is the volume migrated across the grain boundary, r_0 is the softening constant, $\dot{\varepsilon}$ is strain rate, $\dot{\varepsilon}_0$ is the reference strain rate (value is taken as 1), N_r is the number of randomly selected cells in each time step, (# *Rows*)×(# *Columns*) represents the total number of cells in the CA model composed of Rows×Columns, *K* is material constant (value is taken as 6 030).

The dynamic recrystallization adopts the nucleation model proposed by Ding and Guo [5].

$$\dot{n} = C\dot{\varepsilon}^m\left(-\frac{Q}{RT}\right) \tag{5}$$

Table 2 **Parameters of the CA [6,7]**

Parameter	Value
h_0	$5{,}587\times10^{15}$
r_0	329,63764
m	0,12725
Q	89 958,013
K	6 030
Critical dislocation density r_c	$1{,}8028\times10^{11}$ mm^{-2}
Grain boundary migration velocity	$3{,}983\times10^{-7}$mm^4/J/s
Initial dislocation density r_0	0,36 mm^{-2}
Probability of nucleation	0,01
# Rows·# Columns	250 × 250
Initial average grain size	90mm
Elastic shear Modulus	26 518,31MPa
Burgers vector	$2{,}86\times10^{-7}$mm

where *C* and m are material constants, *Q* is activation energy, $\dot{n}$ is nucleation rate, $\dot{\varepsilon}$ is strain rate, T is temperature, and R gas constant.

The microstructure based on the extrusion process is shown in Figure 4, with an average grain size of 90 mm before extrusion (Figure 4a). As the amount of deformation goes up, the dislocations reach a critical density, and fine grains start to form at the trident grain boundaries in 6061 aluminum alloy (Figure 4b). Grain growth leads to grain boundary migration (Figure 4c), which results in a reduction of dislocations and further nucleation growth of new grains. After a certain degree of deformation, the original coarse grains have completely disappeared, and the grains are completely refined (Fig-

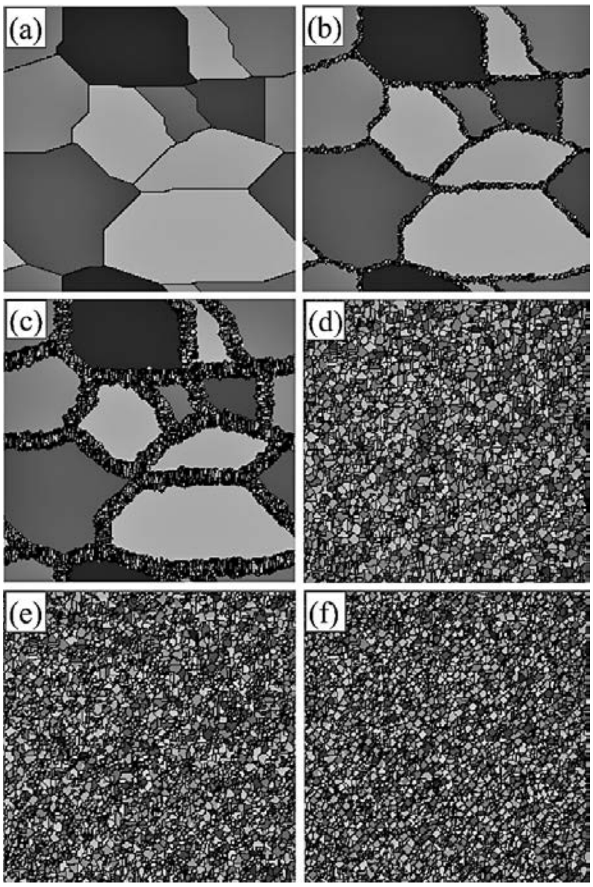

Figure 4 CA simulation based on extrusion process

ure 4d). The billet continues to be maintained above the recrystallization temperature, and the high temperature promotes the growth of fine grains (Figure 4e). Extrusion deformation makes the dislocations continue to accumulate, and when the critical dislocation density is reached, dynamic recrystallization occurs again, producing new fine grains (Figure 4f).

CONCLUSION

From the point of view of numerical simulation, the deformation homogenization of the variable-section hollow shaft extrusion forming process with large depth-to-diameter ratio is high.

Both DRX and CA show how the microstructure changes during the extrusion process. During the extrusion process of the large depth-to-diameter ratio variable cross-section hollow shaft, the initial grains continuously nucleate and grow, which improves the comprehensive mechanical properties of the shaft.

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Note: The responsible translator for English language is Q.D. Zhang, Ningbo, China