Materials Research Proceedings 44 (2024) 144-150 https://doi.org/10.21741/9781644903254-16

Study on microstructural behavior of aluminum alloy thin-walled tube necking formed by three-roll skew rolling

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Keywords: Three-Roll Skew Rolling, Tube, Necking, Secondary Development, Dynamic Recrystallisation

Abstract. To address the issue of incomplete formation of low necking coefficient pipe fittings in hot extrusion processes, this study adopts a novel three-roll skew rolling (TRSR) technique to investigate the microstructural recrystallization distribution patterns during necking forming of aerospace thin-walled pull rods using TRSR. The principles of TRSR necking forming of pipe fittings are initially elucidated, followed by the establishment of a finite element model using simufact forming software and secondary development of the software to embed dynamic recrystallization volume and grain size models. The study analyzes the temperature distribution patterns and dynamic recrystallization behavior during necking forming of aluminum alloy thin-walled pipes via TRSR, aiming to contribute to the research on high-quality necking pipe fittings produced through TRSR.

Introduction

Rod-like fittings are important load-bearing connecting components for aircraft. Traditional processes for manufacturing such necking fittings mainly involve hot extrusion [1], which can lead to defects such as wrinkling, instability, and fracture in the manufactured fittings [2]. Guo et al. [3] analyzed the thickness distribution law by bidirectional extrusion and achieved a maximum deformation necking coefficient of 0.68 by utilizing the temperature gradient coefficient. Yi et al. [4] utilized electric-assisted extrusion to increase the thickness of fittings by up to 300%. However, research on necking forming of these fittings has mainly focused on low necking coefficient fittings obtained through two-stage hot extrusion, resulting in low manufacturing efficiency and the need for improved forming quality. In recent years, researchers such as Pater have employed three-roll skew rolling technology to manufacture axisymmetric components like hollow shafts for trains [5]. Shu [6] conducted a microstructure analysis of the forming process of a 30CrMoA hollow shaft using three-roll skew rolling, revealing the microstructural evolution of the formed part in various deformation stages. Wang et al. [7] discussed the wall thickness quality of three-roll skew rolling (TRSR) hollow shafts from the perspectives of forming mechanism and experimental design. Ye et al. [8] innovatively applied the three-roll skew rolling process to achieve thin-walled fitting necking and thickness increase, analyzing the influence of initial wall thickness on the quality of the formed part through finite element simulation. Xia et al. [9] verified the feasibility of forming aluminum alloy thin-walled fittings using three-roll skew rolling through roller profile design and finite element simulation. However, no one has yet analyzed the microstructural changes in necking forming of thin-walled fittings using three-roll skew rolling. In the rolling process, the more pronounced the refinement of grain size inside the rolled part, the better the quality of the formed part. This paper provides further guidance for high-quality necking fittings formed by three-roll skew rolling through analysis of temperature distribution laws during rolling and dynamic recrystallization grain size and volume fraction.

Principle of three-roll skew rolling forming and necking coefficient

The principle of necking forming for fittings using three-roll skew rolling is shown in Figure 1. It consists of three rolls and a traction clamp arranged in a clover-shaped pattern and offset by 8° from the center axis. The rolls rotate synchronously with the same direction, causing the rolled material to rotate in the opposite direction and giving it a certain axial movement. However, to ensure forming accuracy, the rolled material is also axially moved by the clamp while being synchronously rolled by the upper and lower rolls. In this way, the rolling of the fittings is completed.

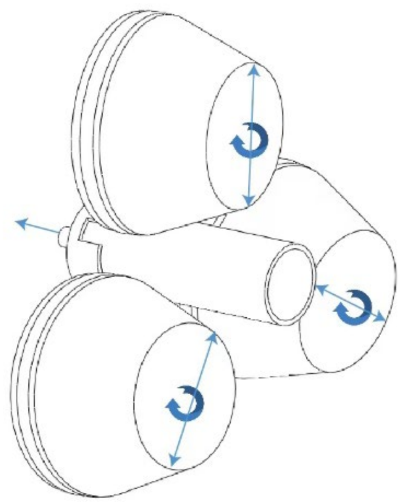

***Figure 1**. The principle of three-roll skew rolling forming*

In order to ensure the reasonable necking coefficient β of the pipe fitting and to guarantee the stable rolling process, there are certain limitations on the vertical movement of the rolls during the rolling process. The distance of roll movement x is related to the roll diameter D and the inner diameter d of the pipe fitting.

The geometric analysis of Figure 1 leads to the following deduction:

$$x < \frac{(\sqrt{3}-2)D}{2} - d \tag{1}$$

$$\beta = \frac{2x}{d} \tag{2}$$

Finite element model for necking forming of three-roll skew rolled pipe

Model establishment.

Firstly, a three-roll skew rolled pipe necking finite element model can be established by creating a 3D model using Solidworks software and saving it in STL format, then importing the model into Simufact Forming finite element software. The model consists of three parts: rolls, billet, and fixture, where the billet and fixture are set to be bonded while the rest are in contact. The billet has dimensions of 32mm × 100mm with a wall thickness of 2mm, and the angle between the roll axis and the billet axis is set to 8°. The roll speed n is 60 rpm, and the friction between the roll and billet is assumed to be shear friction with a coefficient of 0.9. The billet is made of 6061 aluminum alloy and is meshed using sheetmesh. Considering the thin wall thickness of the pipe, four layers of mesh are generated at the wall thickness location, resulting in a total of 8035 initial mesh elements. The empirical constitutive equation for the billet is [10]:

$$\dot{\varepsilon} = 1.1148 \times 10^{21}[\sinh(0.01877\sigma)]^{6.2813} \times exp\left[\frac{-307.528 \times 10^3}{RT}\right]$$

In this formula,
$\dot{\varepsilon}$ is the strain rate (s^{-1});
σ is the stress (Pa);
T is the temperature (°C);
the ideal gas law constant is R = 8.31J/(mol·K).

During the three-roll skew rolling process, the workpiece mainly undergoes plastic deformation. Due to the small amount of elastic deformation, the workpiece is defined as a plastic body, while the roll assembly and fixture are defined as rigid bodies. The initial temperature of the workpiece is set to 300℃, the roll temperature is set to 150℃, the fixture is set to 20℃, and the initial environmental temperature is set to 20℃.

3.2 Secondary development of materials based on empirical ontological modelling

By investigating the relationship between dynamic recrystallization grain size and recrystallization volume fraction model [11] and the deformation temperature, strain rate, as well as strain magnitude in the material forming process, a microstructure evolution model is established for the necking forming process of aluminum alloy thin-walled tube by three-roll skew rolling. Additionally, through secondary development, the model is embedded into simulation for the accurate simulation of dynamic recrystallization in aluminum alloy hot rolling forming process.

Simufact software conducts secondary development by compiling subroutines using the Fortran language. This development integrates dynamic recrystallization grain size model and volume fraction model for 6061 aluminum alloy. It also customizes user variables to facilitate post-processing result analysis.

Table 1. *Custom variables and post-processing results*

Unit variable number	Variable symbol	Reprocessing results
1	DGR	Dynamic recrystallisation grain size
2	DRX	Dynamic recrystallisation volume fraction

Call ueloop and plotv subroutine programming, the dynamic recrystallisation grain size model and recrystallisation volume fraction model will be written into the ueloop subroutine, the parameters are read in a continuous loop, and finally the results of the relevant variables are output through the post-processing of the plotv subroutine, which is partially compiled subroutine as follows:

```
subroutine ueloop(m1,m2,iflag)
implicit logical (a-z)
ccccCalling public module parameters
#include "hards.cmn" !nstats
#include "creeps.cmn" !timinc
#include "arrays.cmn" !iintel
..........
cccDefine initial grain size
dimension grndat(1)
grndat(1)=50
.........
```

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```
cccCalculation of dynamic recrystallisation grain size
drg=119.28*eplas**0.632*erate**(-0.107)*exp((-16540.8)/((incret-273)*8.314))
.........
cccVariable Result Output
subroutine plotv(v,s,sp,etot,eplas,ecreep,t,m,nn,kcus,ndi,nshear,jpltcd)
.........
if(jpltcd.eq.4) v=t(4) !1st user state variable
.........
```

Finite element result analysis

Temperature field distribution of rolled parts.

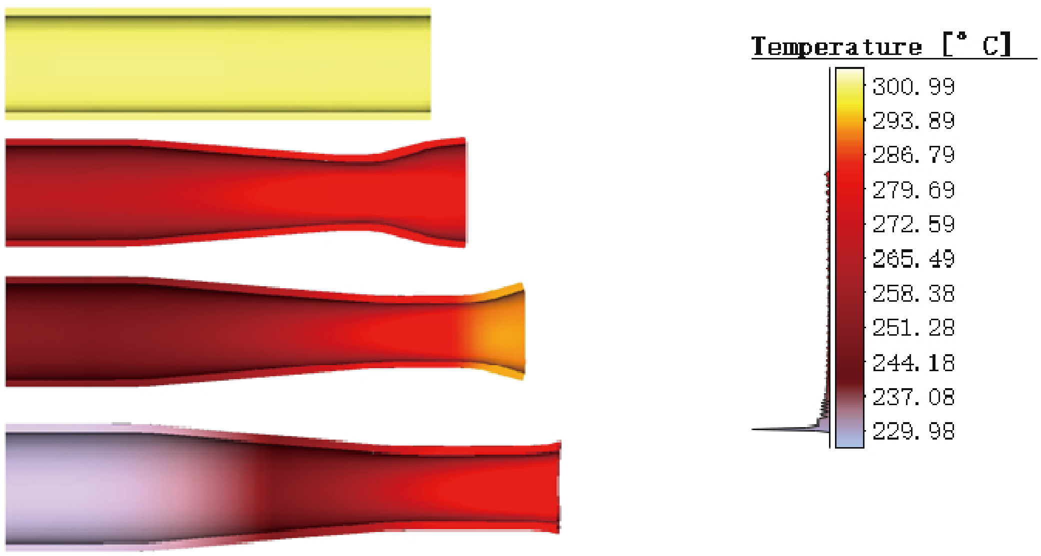
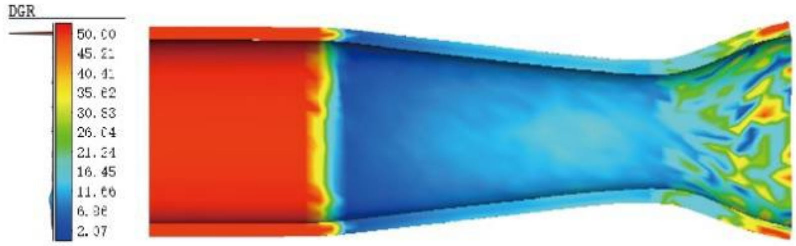


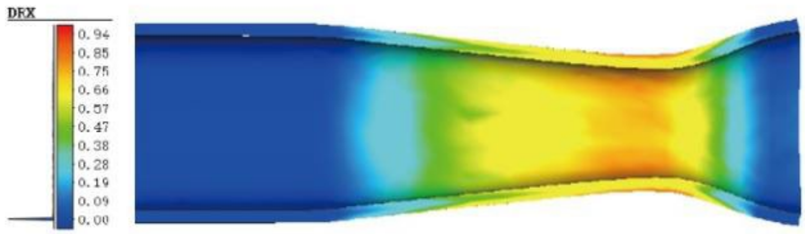
***Figure 1**. Temperature of longitudinal section of the rolled part at each stage*

Figure 2 illustrates the temperature field distribution across the longitudinal cross-sections of the rolled component at different stages. During the rolling of the billet, the temperature decrease is most rapid in the contact area with the fixture, followed by the undeformed end regions, due to the heat conduction from the fixture and the rolling environment. During the necking forming rolling, the temperature of the component gradually decreases as the rolling proceeds, with a decrease of up to 30°C. Once the necking forming is completed, the temperature of the neck region stabilizes at 270°C. As the end of the component is formed, there is a slight increase in temperature within a range of 20°C due to the reduction in necking coefficient. Upon completion of the rolling process, the left end of the component, being in contact with air and the fixture, experiences significant heat dissipation.

Microstructure Distribution in the Necking Forming Section of the Rolled Component.



(a) Distribution of Recrystallized Grain Sizes across the Longitudinal Cross-Section of the Rolled Component



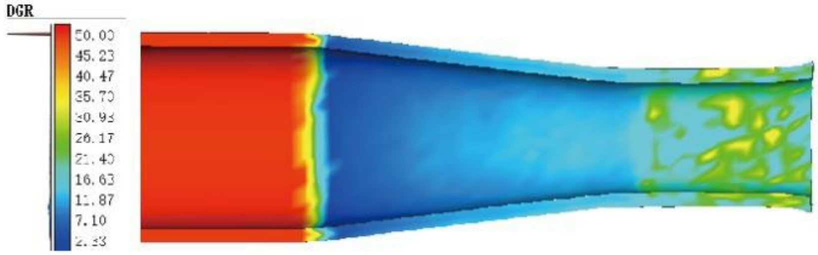
(b) Distribution of Recrystallization Volume Fraction across the Longitudinal Cross-Section of the Rolled Component

Figure 3. *Distribution of Dynamic Recrystallization Grain Sizes and Volume Fraction during the Necking Forming Stage*

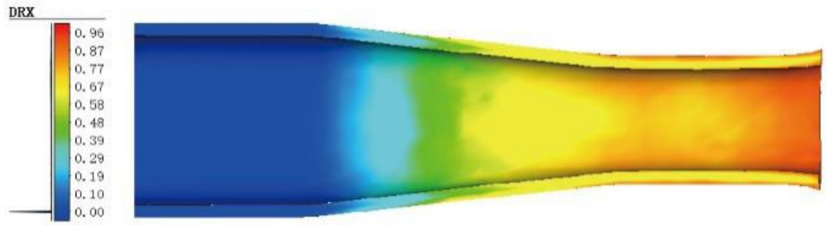
Figure 3 illustrates the distribution of dynamic recrystallization grain sizes and dynamic recrystallization volume fraction across the longitudinal cross-section of the necking forming stage of the rolled component. During this stage, the dynamic recrystallization volume fraction is relatively low at the beginning of the rolling process and gradually increases. A significant grain refinement phenomenon occurs in the necking section of the component, where the grain size decreases from 50μm to as low as 8μm. Dynamic recrystallization mainly occurs in the necking forming area of the component, leading to noticeable grain refinement in the forming region, which gradually permeates from the surface to the core and inner wall of the component. On the right side of the component and in the undeformed end region, the grain size remains at 50μm. The boundary between the deformed and undeformed regions shows a distinct change in grain size, indicating conformity with dynamic recrystallization conditions.

During this stage, the deformation of the component gradually increases, accompanied by an increase in strain rate. The high distortion energy of grain boundaries activates dynamic recrystallization to a greater extent. As a result, the volume fraction of dynamic recrystallization continuously increases during the necking forming stage. By the completion of necking rolling, the recrystallization volume fraction has reached 60%, with even higher values observed on the surface of the component. This is consistent with the conditions conducive to the growth of recrystallized grain sizes.

Microstructure Distribution in the End Forming Section of the Rolled Component.



(a) Distribution of Recrystallized Grain Sizes across the Longitudinal Cross-Section of the Rolled Component



(b) Distribution of Recrystallization Volume Fraction across the Longitudinal Cross-Section of the Rolled Component

***Figure 4**. Microstructural Distribution of Dynamic Recrystallization Grain Sizes and Volume Fraction during the End Forming Stage*

Figure 4 illustrates the distribution of dynamic recrystallization grain sizes and volume fraction across the longitudinal cross-section of the end forming stage of the rolled component. During this stage, as the necking coefficient of the component gradually decreases, the strain increment at the end of the component increases, leading to higher temperatures and intense plastic deformation. Consequently, there is a more pronounced increase in recrystallization grain sizes, with the maximum grain size reaching 34μm at the surface in contact with the rolling mill rolls, and the maximum recrystallization volume fraction reaching 0.97. Upon completion of the rolling process, the dynamic recrystallization grain size refines from an initial 50μm to 10μm, achieving a grain refinement level of 80%. The distribution pattern of dynamic recrystallization grain sizes and volume fraction remains largely consistent throughout this stage.

Conclusion

(1) In the necking forming process of aluminum alloy thin-walled tubes using three-roll skew rolling, the temperature variation is relatively small. However, due to heat conduction from fixtures and air, there is rapid heat dissipation in both the formed and unformed stages of the rolled component. During the rolling stage, the temperature variation of the component is minor, remaining close to the initial temperature.

(2) Three-roll skew rolling for necking forming not only achieves low necking coefficients in a single pass but also results in significant grain size refinement of the component. The degree of grain refinement reaches 80%, thereby enhancing the mechanical properties of the thin-walled tubes.

Acknowledgments

This study was funded by the National Natural Science Foundation of China (grant number: 52375346) and the Ningbo Major Special Project (grant number: 2022Z064).

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