Mechanical properties of steel gun barrel processed by cold radial forging with stepped mandrel under different forging ratios

Yuzhao Yang, Xiaoyun Zhang, Lixia Fan*and Cheng Xu

School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing 210094, China

Email: fanlixia151@njust.edu.cn

Abstract. Mechanical properties of 30SiMn2MoVA steel gun barrel processed by cold radial forging with stepped mandrel under the different forging ratios were investigated in the present work. This work mainly reported the axial and circumferential mechanical properties of forged gun barrel before and after annealing. The axial and circumferential mechanical properties were measured by tensile test and bulging test, respectively. The results suggested that the strength was enhanced and elongation was decreased by forging which was caused by cold work hardening. After annealing, the anisotropy of elongation was observed. The circumferential elongation was weaker than the axial. With the increasing of forging ratios, strength anisotropy was exacerbated gradually. The circumferential strength was inferior to the axial. Besides, there were axial penetrating cracks in the failure state of circumferential bulging test specimens. Through the electron microscopic examination, the axial micro cracks and wrinkles in the inner wall of the forged tubes were observed. It showed that the cold radial forging with stepped mandrel may result in the defect in the inner surface of the gun barrel which should be paid attention.

1. Introduction

Radial forging is an open process to produce tubes and shafts. According to the appearance of the mandrel surface, radial forging also can create internal features of tubes, for example, the rifling of gun barrels. During the process, the diameter and thickness of tube blank will decrease under the pressure of four high-speed hammers. There are many advantages of radial forging, such as high efficiency, high precision, high surface quality and so on. Therefore, the radial forging has become the main process to produce the gun barrel. And it has been investigated for many years. Many researches have been done on radial forging by experiment and numerical simulation. Altan et al. [1] introduced relationships to calculate the stress, required force and other parameters of radial forging. The two-dimensional axisymmetric model [2] and the novel three-dimensional finite element model [3,4] were developed to simulate the radial forging processing. Most studies focused on the process parameters and the deformation of the tube [5-7]. Some researches were carried out about the effect of radial forging on the mechanical properties. Baderestani et al. [8] reported the mechanical properties of W500 tool steel multi-step bars were improved with the increase of strain by radial forging. Arreolaherrera et al. [9] focused on the mechanical properties of 32 CDV 13 steel tube processed and found that the strength and hardness increased with the growth of cold forging ratios. Chen [10]
studied the changes of structure and properties of 30CrNi2MoVA steel thick-walled pipe during cold radial forging through experiments, and further analyzed the changes of hardness and tensile strength of the pipe after cold radial forging. In addition to studying the properties of steel materials, some researchers focused on the titanium alloy. Gubicza J [11] and Hu [12] obtained the same conclusion that the mechanical properties of titanium alloy was increased by radial forging. And gradually, there is a common view that radial forging usually makes changes of the material properties, such as the increased strength and the decreased plasticity. However, most metals with large plastic deformation were anisotropic which has been confirmed in the rolling processing [13,14]. Liu et al. [15] designed a bulging test to obtain the circumferential mechanical properties of the radial forged barrel and proposed the anisotropy in the cold radial forged barrel at first.

This work focused on the mechanical properties of 30SiMn2MoVA steel gun barrel processed by cold radial forging with stepped mandrel under four forging ratios to explore the effect of radial forging on the mechanical properties. Tensile test and bulging test were applied to obtain the axial and circumferential mechanical properties of forged tubes. Meanwhile, electron microscope was employed to check the inner wall of forged tubes to analyze the deformation of material.

2. Materials and methods

The mechanical properties of 30SiMn2MoVA steel were shown in Table 1, which was not forged and was approximated as isotropy.

| Table 1. The mechanical properties of 30SiMn2MoVA steel tube before forged |
|-----------------|-----------------|---------------------|---------------------|-----------------|
| YS/MPa | UTS/MPa | Elongation/% | Reduction of area/% | HRC |
| 958 | 1022 | 15 | 43 | 30~34 |

The internal features are depended on the mandrel. There are two kinds of mandrel in barrel production, round bar mandrel and stepped mandrel. For stepped mandrel, the tube needs to be diameter reduction before wall thickness reduction, as shown in Figure 1. For round bar mandrel, the deformation process of blank tube is only wall thickness reduction. In this work, the cold radial forging with stepped mandrel was investigated and four different forging ratios were set to produce the barrel.

![Diagrammatic sketch of radial forging process with stepped mandrel](image)

Figure 1. The diagrammatic sketch of radial forging process with stepped mandrel

The forging ratios, \( \varphi \), is also called area reduction ratio, which has the following forms

\[
\varphi = \frac{\left( R_o^2 - R_i^2 \right) - \left( R_1^2 - R_2^2 \right)}{R_o^2 - R_i^2} \tag{1}
\]

where \( R_o \) and \( R_i \) are the outer and inner radius of the tube blank, \( R_1 \) and \( R_2 \) are the outer and inner radius of forged tube. For radial forging with stepped mandrel, the forging ratio can be divided into two stage forging ratios, diameter reduction stage \( \varphi_1 \), and wall thickness reduction stage, \( \varphi_2 \), as shown in Figure 1. \( \varphi_1 \) and \( \varphi_2 \) can be calculated by formula (1), the value of radius should be replaced according to the deformation stage mentioned above. There is a relationship between \( \varphi_1 \), \( \varphi_2 \) and \( \varphi \), which is

\[
\varphi = \varphi_1 + \varphi_1 \left( 1 - \varphi_2 \right) \tag{2}
\]
There were four forging ratios for this work and the details were shown in Table 2. After forging, some tubes were annealed at 600 °C for 3h. The aim of annealing is to eliminate the cold work hardening.

| $R_o$/mm | $R_i$/mm | $R_1$/mm | $R_2$/mm | $\phi_1$/% | $\phi_2$/% | $\phi$/% |
|----------|----------|----------|----------|------------|------------|--------|
| 15.075   | 5.825    | 12.235   | 11.640   | 0          | 27%        | 34%    |
| 15.075   | 5.825    | 11.340   | 2.885    | 10%        | 37%        | 47%    |
| 15.075   | 5.825    | 11.015   | 11.015   | 15%        | 38%        | 43%    |

Tensile test was employed to obtain the axial mechanical properties of the tubes according to ASTM E8. The external diameter of tensile specimens is 15mm and the gauge length is 70mm as shown in Figure 2. The tests were carried on a CSS-44100 universal testing machine at room temperature. And the draw speed of machine is 2mm/min.

The bulging experiment was designed by referring to Liu’s work [15]. And the schematic diagram of bulging test is shown in Figure 3. The cylinder specimens are processed by a section of the forged steel gun barrel. Then the polyamine rubber is plugged into the specimen. The two ends of rubber are pressed by a universal testing machine so that the rubber can be compressed. And rubber will transfer the pressure to the inner wall of the cylinder specimen. With the increasing of pressure, the cylinder specimen will bulge. The radial extensometer can obtain the displacement of outer wall of cylinder specimen. The stress of outer wall is calculated according to correlation formulas of stress analysis of thick wall cylinder under internal pressure. The bulging test specimens (a length of 80mm) were cut from the forged tube which was shown in Figure 4. The external diameter of specimen was turned to 9mm so that it can be burst with less pressure.
The forged tubes were cut open along the axial direction. An electron microscope was employed to check the inner surface. Meanwhile the fracture of specimens was also investigated.

3. Results and discussion

3.1. Mechanical properties
The results of tensile test and bulging test are shown in Table 3 and Table 4, forged without annealing and forged with annealing, respectively. The symbol A is axial, T for circumferential.

| Forging Ratio/% | YS/MPa | UTS/MPa | Elongation/% |
|-----------------|--------|---------|--------------|
| 27              | 1001   | 1070    | 1120 | 1144 | 9.50 | 10.10 |
| 34              | 1125   | 974     | 1165 | 1080 | 9.00 | 9.50 |
| 38              | 1129   | 962     | 1168 | 1069 | 8.50 | 8.10 |
| 41              | 1126   | 945     | 1166 | 1043 | 9.00 | 7.45 |

From Table 3, the axial strength values were increased by forging, compared with that before forging (Table 1). When the forging ratio exceeded 34%, there was no dramatic changes in the axial strength values with the increasing of forging ratios. However, the circumferential strength values decreased with the growth of forging ratio, with yield strength changing from 1070MPa (27%) to 945MPa (41%) and tensile strength changing from 1144MPa (27%) to 1043MPa (41%). Comparing the axial and circumferential strength, when the forging ratio exceeded 34%, the circumferential yield strength was lower about 50MPa ~ 80MPa than the axial. Meanwhile the circumferential tensile strength was lower about 80MPa ~ 110MPa than the axial.Forging resulted in the anisotropy of the strength. Besides, the axial and circumferential elongation was 40% ~ 50% lower than that before forging. With the increasing of forging ratio, the circumferential elongation was lower than the axial gradually.

| Forging Ratio/% | YS/MPa | UTS/MPa | Elongation/% |
|-----------------|--------|---------|--------------|
| 27              | 1010   | 1015    | 1073 | 1094 | 15.00 | 11.49 |
| 34              | 1016   | 902     | 1078 | 1022 | 15.00 | 9.06 |
| 38              | 1014   | 861     | 1081 | 973  | 15.50 | 8.51 |
| 41              | 1019   | 857     | 1089 | 957  | 15.50 | 7.91 |

When it turned to Table 4, the axial and circumferential strength values were decreased by annealing comparing with Table 3. There was not much difference in axial strength under different forging ratios. However, the circumferential strength was still decreased with the increasing of the forging ratios and it was smaller than the axial. Under 41% forging ratio, the circumferential yield strength was lower 15.89% than the axial. And the circumferential tensile strength was 12.12% lower than the axial. The axial elongation was restored to about 15% by annealing. Whereas the circumferential elongation was not restored. The elongation appeared remarkable anisotropy. The circumferential elongation was 30% ~ 50% lower than axial.
In order to describe strength anisotropy intuitively, the strength ratio was calculated as shown in Figure 5 and Figure 6, which was yield strength ratio and tensile strength ratio, respectively. When the ratio was 1, the material was isotropy.

![Figure 5](image)

**Figure 5.** The axial and circumferential yield strength ratio

From the Figure 5, under 27% forging ratio, the steel gun barrel was isotropy approximatively. Because the yield strength ratio was 0.995, which was close to 1. With the growth of forging ratio, the anisotropy was gradually obvious. The yield ratio under 41% forging ratio was 19.8% larger than that under 27% forging ratio after annealing. The circumferential was inferior to the axial. The annealing cannot change the anisotropic phenomenon. Because the yield strength ratio was almost the same under 38% (1.178 and 1.174) and 41% forging ratios (1.192 and 1.189) before and after annealing.

![Figure 6](image)

**Figure 6.** The axial and circumferential tensile strength ratio

For the tensile strength ratio, from the Figure 6, it had the same trend as the yield strength ratio. With the increasing of the forging ratio, the anisotropy became obvious. After annealing the anisotropy was a little stronger than before annealing under 38% and 41% forging ratios.

For further analysis, the strain ratio \((ε_r/ε_θ)\) was introduced to investigate the influence of forging ratio on anisotropy of plasticity. \(ε_r\) is axial strain while \(ε_θ\) is circumferential strain. It can be calculated by \(\ln(l_i/l_0)/\ln(D_1/D_0)\) where \(l_0\) and \(l_i\) are the length of tensile specimens before and after tensile test. \(D_0\) and \(D_1\) are the outer diameter of cylinder specimens before and after bulging test. Ideally, the strain ratio of isotropic material equals one. When the value of strain ratio is greater than 1, it indicates that axial plasticity is better than circumferential. Conversely, if it less than 1 the axial plasticity is weaker than circumferential. The result of strain ratio after annealing under different forging ratios is shown in Figure 7. The values of strain ratio have an increasing trend which suggests that the anisotropy is gradually obvious with the growth of the forging ratio. The forging processing under different ratios made a significant effect on mechanical properties of 30SiMn2MoVA high strength steel gun barrel, especially plasticity. Before annealing, the anisotropy was not too strong. Nonetheless, after annealing
anisotropy was aggravated. For forging ratio 41%, the value of strain ratio after annealing was 58% higher than before annealing. And the strain ratio of forging ratio 41% was 47% higher than that of forging ratio 27% after annealing.

![Figure 7. The axial and circumferential stain ratio](image)

3.2. Fracture analysis

There was an interesting phenomenon drawing the attention which was the failure state of bulging test specimens as shown in Figure 8. Before annealing, there were penetration cracks in the specimens. With the increasing of forging ratio, the failure state was severe. When the forging ratio were 38% and 41%, the specimen was divided completely into two parts under internal pressure. After annealing, although there were no penetrating cracks, the length of crack was longer than the failure state of before forging. And that was increased with the growth of forging ratios.

| Before forging | φ/°%  | 27 | 34 | 38 | 41 |
|----------------|-------|----|----|----|----|
| Before annealing | ![Image](image) | ![Image](image) | ![Image](image) | ![Image](image) | ![Image](image) |
| After annealing | ![Image](image) | ![Image](image) | ![Image](image) | ![Image](image) | ![Image](image) |

![Crack length](image)

**Figure 8.** The failure state of specimens after bulging test

Through the fracture analysis of bulging test specimen, as shown in Figure 9, it was quasi cleavage fracture which was between the cleavage fracture and dimple fracture. Large plastic deformation
appeared on the fracture surface, which was characterized by tearing ridges formed due to the propagation of small cracks in several places. The traces of crack extension were clear along the axial direction. It showed that there were cracks in the forged tubes with stepped mandrel, which was confirmed by Figure 10. There were many cracks in the inner surface of bulging test specimen.

The fracture morphology of bulging test specimen

The inner surface of bulging test specimen

The fracture morphology of tensile test specimen was obviously different from the bulging test specimen as shown in Figure 11. The macroscopic appearance was fibrous and the fracture morphology was dimple fracture which showed that the cracks were only on the inner surface.

The forged steel gun barrel was cut open to check the inner surface quality. The Figure 12 showed the inner surface of diameter reduction stage in which there was no contact between tube and mandrel. Many wrinkles were observed along the axial direction. When the tube contacted the mandrel (wall thickness reduction stage), there were many wrinkles and cracks as shown in Figure 13. The cracks may be formed due to the existence of wrinkles. While it needed further study about the formation mechanism of wrinkles and crack on the inner surface during forging. However, it can be determined that the radial forging with stepped mandrel may cause wrinkles and cracks defect on the inner surface of the forged gun barrel.
4. Conclusions
The present work concentrated on the mechanical properties of cold radial forged steel gun barrel with stepped mandrel. Four forging ratios were set to process gun barrel. Tensile test, bulging test and electron microscope were employed to obtain the axial mechanical properties, circumferential mechanical properties and microstructure, respectively. The main results are as follows:

(1) With the increasing of forging ratios, the anisotropy became obvious whether before or after annealing. The circumferential strength was inferior to the axial.

(2) After annealing, the circumferential elongation was 30% ~ 50% lower than axial. With the growth of forging ratios, the strain ratio became larger.

(3) The fracture morphology of bulging test specimen was quasi cleavage fracture while the fracture of tensile test specimen was dimple fracture. The axial wrinkles and cracks were observed on the inner surface of the forged gun barrel which showed that the radial forging with stepped mandrel may result in the detects of forged gun barrel.

Acknowledgments
This work was supported by the National Defence Basic Scientific Research Program of China (JCKY2016209A002). Microcosmic experiment was performed at the Materials Characterization Facility of Nanjing University of Science and Technology.

References
[1] Altan T, Boulger F W, Becker J R, Akgerman N and Henning H 1973 Forging equipment, materials and practices
[2] Lahoti G and Altan T 1976 Analysis of the radial forging process for manufacturing rods and tubes. ASME. J. Eng. Ind. 98 265-71
[3] Ghaei A and Movahhedy M R 2007 Die design for the radial forging process using 3D FEM J. Mater. Process. Tech. 182 534-39
[4] Fan L, Wang Z and Wang H 2014 3D finite element modeling and analysis of radial forging processes J. Manuf. Process. 16 329-34
[5] Sanjari M, Karimi Taheri A and Ghaei A 2007 Prediction of neutral plane and effects of the process parameters in radial forging using an upper bound solution J. Mater. Process. Tech. 186 147-53
[6] Sanjari M, Taheri A and Movahedi M 2009 An optimization method for radial forging process using ANN and Taguchi method Int. J. Adv. Manuf. Tech. 40 776-84
[7] Liu L and Fan L 2009 Study of residual stresses in the barrel processed by the radial forging 2nd Int. Conf. on Information and Computing Science (IEEE Computer Society) 131-34
[8] Baderestani M, Hosseini M and Hanzaki A 2004 The evaluation of microstructure and mechanical properties of w500 tool steel during radial forging practices.
[9] Cruzramirez A and Suárezrosales M 2014 The effect of cold forming on structure and properties of 32 cdv 13 steel by radial forging process Mat. Res. 17 445-50
[10] Chen H, Wu H, Chen X and Zhang L 2013 Microstructure and properties of the 30CrNi2MoVA steel thick-walled tubes prepared by cold radial forging Heat Treat. Met. 38 56–9
[11] Gubicza J, Fogarassy Z and Králícs G 2008 Microstructure and mechanical behavior of ultrafine-grained titanium Mat. Sci. Forum 589 99-104
[12] Hu XD 2014 Microstructure evolution and mechanical properties of TC4 titanium alloy in precision forging process Hot Working Tech. 23 157-59
[13] Liu Y, Mao P, Zhang F, Liu Z and Wang Z 2018 Effect of temperature on the anisotropy of AZ31 magnesium alloy rolling sheet under high strain rate deformation Philos. Mag. 98 1068-86
[14] Leacock A 2012 The future of sheet metal forming research. Mater. Manuf. Process. 27 366-69
[15] Liu L, Fan L and Dong X 2012 Experimental study of the mechanical property of barrel processed by cold radial forging J. B. Inst. Technol. 21 453-59