Analysis of the Tungsten Wire-Drawing Process

タングステンワイヤー線引き工程の解析

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キーワード： タングステンワイヤー，FEM 解析，伸線加工，リダクション角度，ベアリング長さ，ワイヤー温度，引き抜き荷重

Abstract

Tungsten wire is processed by pulling the hot wire through a die at a high temperature. However, this technique is associated with several issues, including longitudinal crack formation and wire diameter reduction. Analyzing the plastic deformation behavior of wire, such as strain and stress, when passing through a die is crucial for the production of high-quality wire. In this study, we created a numerical simulation model using finite element method analysis to simulate high-temperature wire drawing, and compared it with the actual wire-drawing process to verify the validity of the simulation. We successfully reproduced the drawing process of tungsten wire via this simulation analysis. We then visualized the changes in the drawing load and strain distribution in the wire by changing the internal shape of the die and processing conditions. Simulations considering various parameters of the actual wire-drawing process must be conducted to further improve the quality of drawn tungsten wires. This study lays a foundational basis for the validity of simulation analysis for actual wire-drawing processes.

タングステンワイヤーの伸線加工は，ワイヤーを熱間でダイスに通して引抜く高温引抜きによって行われる．伸線加工の不具合例として，伸線加工時に発生する長手方向の割れ（クラック）や線径細りが挙げられる．高品質なワイヤー製造のためには，ダイスを通過する際のひずみや応力といった塑性変形での挙動解析が重要となる．

本研究では，実際の高温引抜きを模した数値シミュレーションモデルを FEM 解析にて作成し，実際の伸線加工と比較を行い，シミュレーションの有効性を検証した．

その結果，タングステンワイヤーの伸線加工をシミュレーション解析で再現することができた．また，ダイス内部形状や加工条件を変更した解析では，ワイヤーの引き抜き荷重やひずみ分布の変化を可視化できた．タングステンワイヤーの伸線加工における更なる品質向上のためには，実際の伸線加工の様々なパラメーターを考慮したシミュレーションを検討する必要がある．本研究では，実際の伸線加工に関するシミュレーション解析の基礎を検討することができた．

1. Introduction

Tungsten wire is processed by wire drawing; in this technique, the wire is pulled through a die at a high temperature. However, this technique is associated with several issues, including the occurrence of longitudinal cracks during the drawing process and a reduction in wire diameter after passing through the die. For the production of high-quality wire, it is important to analyze the plastic deformation behavior of wire, such as strain and stress, when passing through a die.

In this study, we examined the causes of these issues, predicted other potential defects that may occur during wire drawing, and considered appropriate countermeasures. Specifically, we created a numerical simulation model to simulate the actual high-temperature wire-drawing process and investigated the strain and temperature distributions along the wire.

2. Analysis of the tungsten wire-drawing process

2.1 Construction of a tungsten wire-drawing model by finite element model analysis

The tungsten wire-drawing process was simulated by finite element model (FEM) analysis. The wire-drawing model is shown in **Fig. 1**. In this analysis, we adopted a model in which the die used in the wire-drawing process was fixed and the wire was held by a holder and then pulled out. The wire moves from top to bottom in **Fig. 1**. The parts of the die are identified in **Fig. 2**.

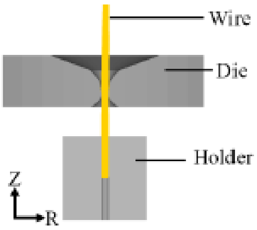

Fig. 1 Simulation model

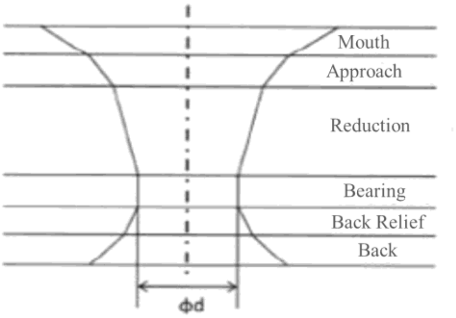

Fig. 2 Internal structure of the die

2.2 Analysis of the die internal shape and wire-drawing load

First, we analyzed the die internal shape and drawing load during the wire-drawing process. Simulation analysis of the die internal shape was performed by changing the values of the reduction angle and bearing length, which are factors considered to have the greatest effect on the wire-drawing process. **Table 1** lists the values adopted for these properties. The wire used in the simulation analysis had a diameter of φ0.19 mm before drawing and φ0.17 mm after drawing (reduction ratio: 20%). The wire temperature was set to 700 °C.

Table 1 Internal shape conditions of the dies

Reduction angle (°)	6, 8, 10, 14, 17, 19
Bearing length (mm)	0.15d, 0.3d, 0.4d, 0.5d, 0.6d

The simulation results of the relationship between the reduction angle and wire-drawing load (in the Z-axis direction) are shown in **Fig. 3**. The bearing length was fixed at 0.4d, with d being the inner diameter of the die. According to the results, the wire-drawing load was smallest near a reduction angle of 10° and increased at other reduction angles.

The simulation results of the wire-drawing load (in the Z-axis direction) versus the bearing length are shown in **Fig. 4**. Here, the reduction angle was fixed at 17°. According to the results, the bearing length remained constant regardless of the wire-drawing force.

Fig. 5 shows the simulation results for the correlation between the reduction angle and wire diameter after drawing. The bearing length was fixed at 0.4d. The wire diameter decreased as the reduction angle increased. Although we expected to find a peak in the wire diameter at a certain reduction angle, similar to the relationship with the drawing load shown in **Fig. 3**, this tendency was not confirmed in the present analysis.

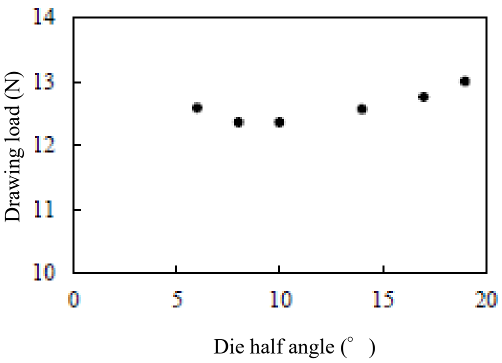

Fig. 3 Correlation between the reduction angle and drawing load

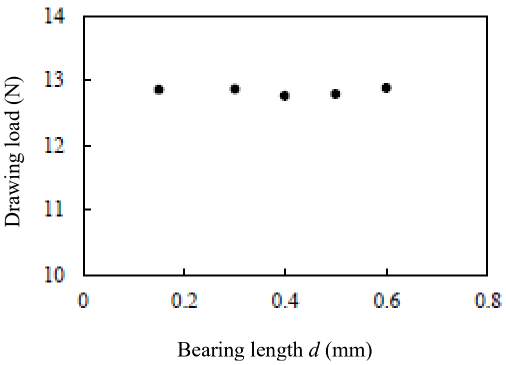

Fig. 4 Correlation between the bearing length and drawing load

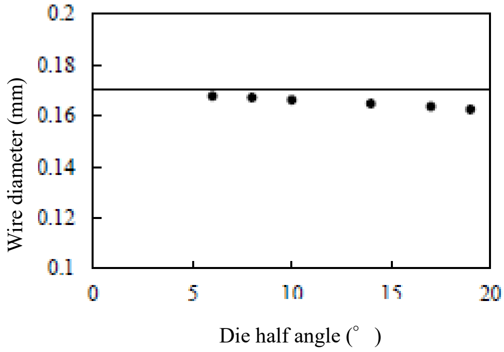

Fig. 5 Correlation between the reduction angle and wire diameter after drawing

2.3 Analysis of die shape measurement results and wire-drawing process

Next, the internal shape of the wire-drawing die was measured, and simulation analysis was conducted using the measured values. We used CU11, a die shape-measuring instrument manufactured by Conoptica, to measure the internal shape of the die.

The conditions for the die internal shape are shown in **Table 2**. The wire used in this simulation analysis had a diameter of φ0.19 mm before drawing and φ0.17 mm after drawing (reduction ratio: 20%).

The simulation results of the relationship between the reduction angle and temperature increase during wire drawing are shown in **Figs. 6 and 7**. The initial temperature was set to 700 °C. We confirmed that the temperature increase during drawing increased as the reduction angle increased.

The variation in shear strain with the distance from the center of the wire cross-section is shown **Fig. 8**; here, the horizontal axis represents the radial distance from the center of the wire cross-section. A difference in strain between the outer periphery and center of the wire was observed when the wire was drawn using a die with a large reduction angle. This difference in strain can lead to residual stress during the wire-drawing process, resulting in the occurrence of cracks on the wire surface. Hence, the reduction angle must be decreased to reduce the difference in strain inside the wire.

Table 2. Die internal shape conditions

No.	Reduction angle	Bearing length
1	7.8	0.58d
2	24	0.28d
3	20	0.45d
4	18.5	0.23d
5	10.8	0.37d

The correlation between the initial wire temperature and drawing load (in the Z direction) is shown in **Fig. 9**. According to this figure, the drawing load decreases as the initial wire temperature increases. Additionally, the effect of the die internal shape on the drawing load is low. The correlation between the initial wire temperature and wire diameter after drawing is shown in **Fig. 10**. The effect of the initial temperature on the wire diameter after drawing was small.

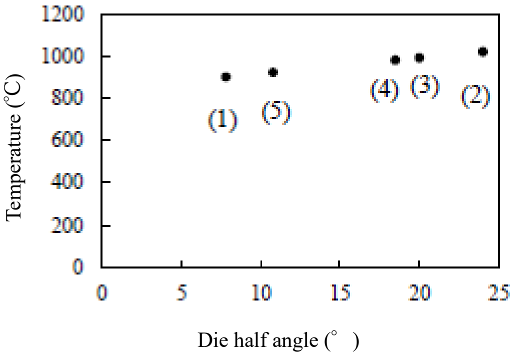

Fig. 6 Correlation between the reduction angle and temperature rise during wire drawing

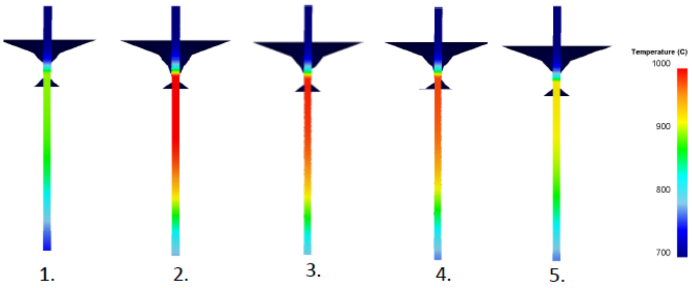

Fig. 7 Simulation results of the reduction angle and wire temperature

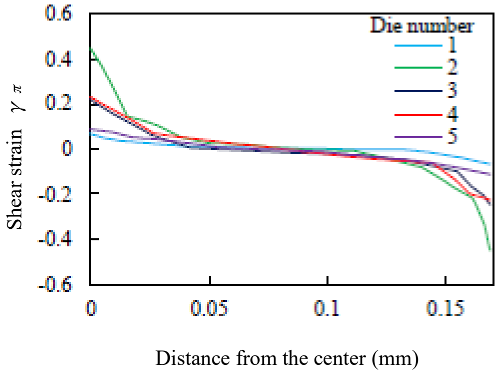

Fig. 8 Correlation between the distance from the center of the wire cross-section and shear strain

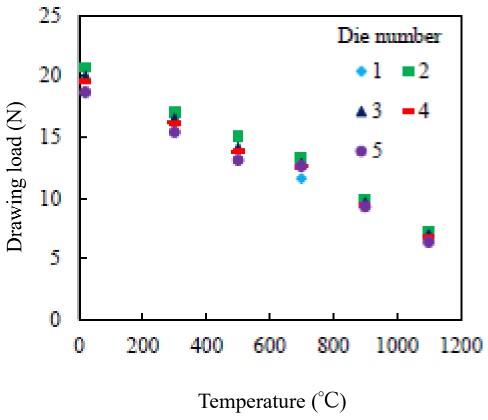

Fig. 9 Correlation between the wire temperature and drawing load

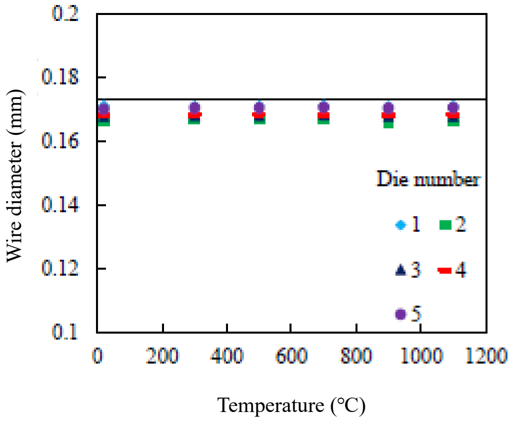

Fig. 10 Correlation between the wire temperature and wire diameter **drawing**

3. Comparison between the numerical simulation analysis and actual processing

To compare the simulation results obtained in Sections 2-2 and 2-3 with the actual wire-drawing process, we used the dies whose shapes were measured to draw tungsten wires.

The correlation between the reduction angle and size difference (i.e., between the die hole diameter and wire diameter after drawing) is shown in **Fig. 11**, and the correlation between the bearing length and size difference is shown in **Fig. 12**.

As shown in **Fig. 11**, the size difference is smallest when the reduction angle is between 8° and 10°. This finding suggests that the thinning of the wire diameter during the wire-drawing process is less likely to occur within this range. The simulation results depicted in **Fig. 3** also indicate that the drawing load is lowest around a reduction angle of 10°. Comparing the simulation results with the actual wire-drawing process, we believe that reductions in wire-drawing load and residual tensile stress on the tungsten wire will render wire-diameter thinning unlikely to occur.

We also confirmed that the size difference is minimized at approximately 0.4d–0.5d of the bearing length. Although the simulation results in **Fig. 4** indicate that the effect of the bearing length on the wire-drawing process is small, we believe that the bearing length must be considered during actual wire drawing.

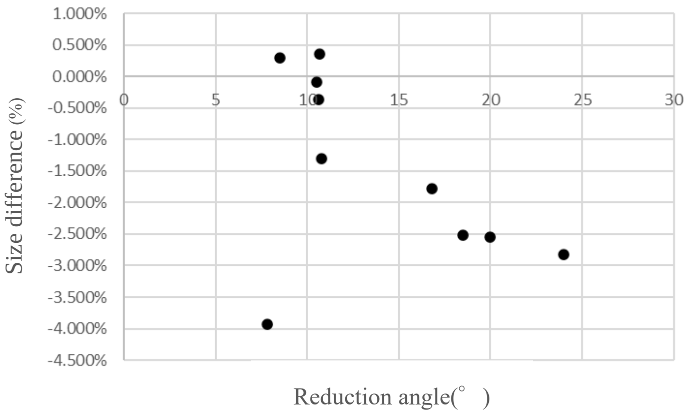

Fig. 10 Correlation between the reduction angle and size difference

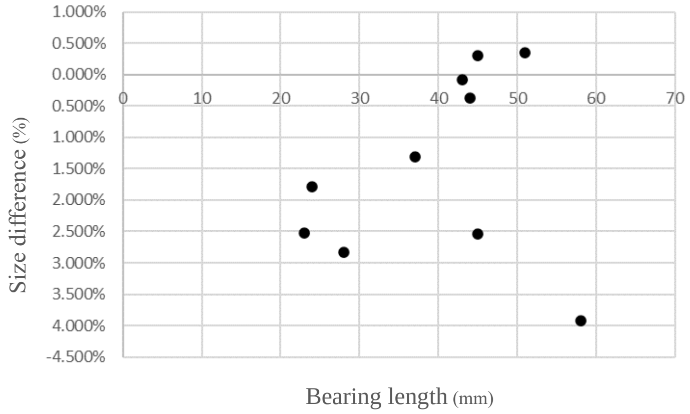

Fig. 11 Correlation between the bearing length and size difference

4. Conclusions

In this study, we replicated the drawing process of tungsten wire using FEM analysis. We successfully visualized the changes in the wire-drawing load and strain distribution by modifying the internal shape of the die and processing conditions.

The cracks and reduction in wire diameter that occur during actual wire drawing are caused by a complex interplay of various factors, including the residual tensile stress that exists on the wire surface after passing through the die and frictional forces that occur between the die and wire. Hence, the various parameters present during actual wire drawing must be considered to improve the accuracy of the simulation and further enhance the quality of the tungsten wire-drawing process.

Tungsten wire, a high-melting-point material, undergoes drawing processing at elevated temperatures. However, simulating this process is challenging due to the impact of factors such as wire temperature on quality. This poses a limitation to our study.

Although several challenges must be overcome to accurately quantify the residual stress and lubricity of the wire, this study provides a basis for the simulation analysis of the drawing process of tungsten wire. In the future, we aim to quantify the factors affecting the drawing process of tungsten wire and develop the simulation.