General paper

A Study on the Influence of Mechanical Properties on the Distribution of Axial Residual Stress after Cold Drawing of Metallic Bars

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Abstract: Investigation was carried out on the influence of mechanical properties on the intensity of axial residual stress after cold drawing of metallic bars. Yield stress, Young's modulus, and work-hardening ratio were chosen as indications of mechanical properties, and quantitative influence was examined numerically on an ordinary cold drawing. After examining the quantitative influence of mechanical properties on the axial residual stress after drawing, further numerical experiments were carried out on the skin-pass effect in reducing the intensity of axial residual stress distribution, which the authors presented a result in the previous study by using S45C steel bars. In order to clarify the validity of the numerical analysis, various materials of different mechanical properties were selected, and cold drawing experiments were carried out in a laboratory to check the validity of the numerical results. The materials selected were (1) high-carbon steel, (2) medium carbon steel, (3) copper, and (4) aluminum. The residual stress was measured by Sachs method, and good agreement was obtained between the calculated and measured results in any case. It was found that the axial residual stress distribution is most sensitive to the work-hardening ratio, and an optimum skin-pass drawing condition was presented by quantitatively examining the effect of skin-pass in reducing the axial residual distribution.

Key words: *Drawing, Residual stress, Mechanical properties, Skin pass*

1. INTRODUCTION

It is known that the residual stress plays an important role in determining the final geometry of cold-worked metallic products. There is an increasing demand from the market that the cold-worked products be supplied to the customer without any finishing process for reducing the residual stress in order to ensure the product geometry. In other words, sensitivity to the manufacturing cost has been increasing. There are studies on the evaluation of the residual stress in the cold-worked products [1,2], and also on the optimum tool geometry in minimizing the residual stress after cold drawing [3]. However, in these references attention has been focussed on only one material, and few investigations have been carried out on the quantitative evaluation concerning the influence of mechanical properties of materials.

In the manufacturing process, there are two cases of treatment where only one material is treated, and where various materials are treated consecutively using the same die. In the former case, there is no need for evaluating the influence of the difference in material properties on the residual stress. In the latter case, however, it is important to understand the quantitative influence of the difference in material properties on the residual stress, because it may lead to a decision whether to adopt a different process for specific materials. This viewpoint is important on the manufacturing side, because decisions concerning the manufacturing process directly influence the manufac-

turing cost.

In the present study, the cold drawing process was taken as an example, and the influence of mechanical properties of material on the residual stress after drawing was studied by carrying out numerical and laboratory experiments. After determining the quantitative effect of mechanical properties of material on the residual stress by a single-die drawing, the influence of mechanical properties on the skin-pass effect was studied in detail. The skin-pass effect was proposed and studied by the authors previously [4].

2. ANALYSIS OF A SINGLE-DIE DRAWING

It is important to define the factors which adequately describe the mechanical properties of materials in carrying out numerical analyses. In the present study, three factors were taken to describe the mechanical properties: (1) Young's modulus E , (2) Yield stress σ_e , and (3) Work-hardening ratio H , which are illustrated in Fig. 1.

As for the values of these factors, those for a medium-carbon steel were selected as standard values, namely

Table 1. Range of mechanical properties of material.

	Young's modulus E / MPa	Yield stress σ_e / MPa	Work-hardening ratio H / MPa
Standard values	200,000	400	3000
Deviation	$\pm 100,000$	± 200	± 3000

Fig. 1. Definitions of three mechanical properties of material.

$E=200,000\text{MPa}$, $\sigma_e=400\text{MPa}$, and $H=3000\text{MPa}$ with equal plus-minus deviations, as shown in Table 1.

The die geometry was selected to have a commonly used die angle, and reduction in area was so selected as to meet the ordinary medium reduction. The details are indicated in Table 2.

The code used for the numerical analyses was "ELFEN", which was developed at the University of Wales, Swansea, and elastic-plastic analyses were carried out. An example of the finite element mesh is shown in Fig. 2. The results are indicated in Fig. 3. Noteworthy is that only the work-hardening ratio H has a strong influence on the distribution pattern of axial residual stress, and the other two factors, Young's modulus E and yield stress σ_e , have little influence on the residual stress distribution.

Table 2. Conditions for numerical experiments on single-die drawing.

Die geometry	Die angle $\theta / ^\circ$	14
	Inside diameter d / mm	$\phi 30$
	Bearing length B / mm	6
	Reduction / %	17.4
Mother bar	Inlet diameter / mm	$\phi 33$

Fig. 2. Example of finite element mesh for numerical analysis.

Fig. 3. Influence of mechanical properties on the axial residual stress distribution after single die drawing.

3. LABORATORY EXPERIMENTS

Laboratory experiments were carried out in order to check the validity of the numerical analyses. Stress-strain curves for various materials were first measured, and then the axial residual stress was measured using Sachs method [5,6] after cold drawing in order to compare the results with the numerical ones.

3.1. Preliminary Experiments

Table 3 shows the list of materials selected and the details of specimen preparation. The specimens were subjected to tension test, and stress-strain curves were measured. The results are illustrated in Fig. 4. It is shown that high-carbon steel AISI1110 has the highest work-hardening ratio, and aluminum has the lowest among the materials supplied for the tension test. It is assumed that

there will be a big difference in the measured residual stress between these two materials.

3.2. Drawing Experiments and Measurement of Residual Stress

The materials, after being annealed under the condition given in Table 3, were subjected to cold drawing using the draw bench and die shown in Fig. 5.

The drawing conditions are given in Table 2. Specimens of specific length were cut from the drawn bars and were subjected to the measurement of residual stress by the Sachs method, of which the detailed procedure and a sample specimen are indicated in Fig. 6. In order to suppress the influence of drilling on residual stresses, the

Table 3. Conditions of specimen preparations for tension test.

Materials	Annealing condition
High carbon steel (AISI1110)	1023 K × 2hr and cooled in furnace
Middle carbon steel (AISI1045)	923 K × 2hr and cooled in furnace
Copper	773 K × 2hr and cooled in furnace
Aluminum	673 K × 2hr and cooled in furnace

Fig. 4. Results of tension test.

Fig. 5. Drawing apparatus and die geometry.

Fig. 6. Procedure of Sachs method and specimen.

Table 4. Measured changes in strain by Sachs method.

	Material*	Diameter of drill holes d_z / mm					
		10	15	18	21	24	27
Axial strain $\times 10^{-6}$	H	-477	-1012	-1284	-1720	-1880	-1763
	M	-385	-802	-1072	-1389	-1607	-1626
	C	-227	-453	-584	-760	-761	-561
	A	-77	-200	-236	-287	-150	-125
Circumferential strain $\times 10^{-6}$	H	-218	-519	-725	-1009	-1230	-1479
	M	-236	-508	-646	-870	-1071	-1283
	C	-150	-289	-379	-475	-546	-563
	A	-43	-93	-116	-111	-6	8
Residual stress / MPa	H	-933	-433	-124	216	444	534
	M	-745	-369	-122	135	343	456
	C	-231	-95	-11	72	118	110
	A	-60	-18	4	25	24	22

* H: High carbon steel M: Medium carbon steel
C: Copper A: Aluminum

Fig. 7. Comparison of axial residual stress distribution among different materials.

start hole, drilled at less than specified diameter d_z by 1mm in advance, was enlarged using boring tool. The specimen was rotated at 115rpm against the boring tool. The measured changes in strain are given in Table 4.

3.3. Results

The estimated results of the residual stress from the changes in the measured strain by the Sachs method were compared with the predicted ones by numerical analyses in Fig. 7. The matching between the two is excellent, and

it may be concluded that numerical experiments predict well the axial residual stress distribution in the cross section. As was predicted by the analyses, the higher the work-hardening ratio is, the wider the distribution pattern of residual stress is. These results support the hypothesis proposed through the numerical experiments that the work-hardening ratio H has strong influence on the residual stress distribution.

4. INFLUENCE OF MECHANICAL PROPERTIES ON SKIN-PASS EFFECT

The authors have proposed a method of "skin-pass drawing" which remarkably reduces the axial residual stress [4]. The outline of this method is such that the installation of a drawing with small reduction in area up to a few percent maximum at final stage of two-pass drawing reveals a prominent effect in leveling the axial stress distribution in the cross section.

The mechanism through which the remarkable flattening effect appears is given in Fig. 8 in a simplified manner. During the first pass, the stress states of the center portion C and the surface portion S change as $O \rightarrow Y \rightarrow S1 \rightarrow S2$ and $O \rightarrow Y \rightarrow C1 \rightarrow C2$ respectively in Fig. 8. After the first pass, the center portion C and the surface portion S elastically balance so as to have the same longitudinal strain. Although the equivalent plastic strain due to drawing is larger in the portion S compare to the portion C, the longitudinal plastic strain is smaller in the portion C. As a result, the longitudinal stress in the portion C becomes compressive and the stresses are S2 and C2 at the balancing point.

When the reduction in area at the second pass R_{d2} becomes small enough for the portion S to enter slightly into the plastic zone as $S2 \rightarrow S1 \rightarrow S3$, the portion C remains in the elastic stage as $C2 \rightarrow C3$, because the portion C is initially compressive and the strain is not large enough for the portion C to enter the plastic zone. After the second pass, mechanical balance is also achieved through the same mechanism as the first pass, and the difference in the longitudinal stress between the portions C and S is smaller after the second pass as S4 and C4. As a result the residual stress distribution becomes flat. This method is of industrial importance, and it is valuable to carry out quantitative analyses on the influence of material properties on the skin-pass effect.

Fig. 8. Schematic illustration on the mechanism of skin-pass effect.

Numerical experiments were first carried out in a similar manner as those in the previous section under such conditions as shown in Table 5. The results in Fig. 9 show that the leveling effect of axial residual stress by skin-pass drawing highly depends upon the work-hardening ratio H , similar to the previous results for the single-die drawing, while the other two factors, Young's

Table 5. Conditions for numerical experiments on the influence of mechanical properties on skin pass effect.

Die geometry	1st pass	2nd pass	Notes
Die angle $\theta / ^\circ$	14	14	
Inside diameter d / mm	$\phi 30$	$\phi 27 - \phi 29.99$	
Bearing length B / mm	6	6	
Reduction / %	17.4	0.07-19.0	Total = 17.4-33.1
Mother bar diameter / mm	$\phi 33$		
Coefficient of friction	0.07

(a) Young's modulus

(b) Yield stress

(c) Work-hardening ratio

Fig. 9. Influence of mechanical properties on skin pass effect.

modulus E and yield stress σ_y , have little influence.

In order to evaluate quantitatively the intensity of axial residual stress, an index defined by Eq. (1) was introduced. As the distribution pattern of axial residual stress is such that it is compressive at the center and tensile in the vicinity of the surface, the smaller this index is, the flatter the pattern is.

$$\text{Index} = \int_0^{d/2} 2\pi |\sigma_z| r dr, \quad (1)$$

d : Diameter
 σ_z : Axial residual stress
 r : Distance from center

By using this index, the influence of work-hardening ratio H on the skin-pass effect was investigated in such domain that the reduction for the second pass falls within a reasonable range. The result is shown in Fig. 10. It is important to note that the larger H is, the larger the index is, which means that the skin-pass effect becomes smaller as the work-hardening ratio becomes larger. However, it is noticeable that the optimum condition is almost independent of H , and it lies in the vicinity of the point where the reduction in area on the skin-pass is 1.0%.

Fig. 10. Influence of work-hardening ratio on the skin pass effect.

5. VALIDATION OF NUMERICAL ANALYSIS

In order to check the validity of the numerical results in the previous section, laboratory experiments were carried out on an ordinary single-pass drawing and also on a skin-pass drawing. Two materials were selected, one of which had a larger work-hardening ratio in comparison with the other. The drawing conditions are given in Table 6.

After drawing, the axial residual stress was measured using the Sachs method in the similar manner as in the previous section. The results are shown in Fig. 11. Matching of the numerical results with the experimental ones is excellent, and it can be concluded that numerical analyses predicted well the residual stress. Although the effect of skin-pass drawing is clear, as it was predicted,

Table 6. Conditions of skin pass drawing for validity check of the numerical analysis.

	Case 1	Case 2		Case 3	
Number of passes	1	2		2	
Die geometry	1st pass	1st pass	2nd pass	1st pass	2nd pass
Die angle $\theta / ^\circ$	14	14	14	14	14
Inside diameter d / mm	$\phi 30$	$\phi 30.1$	$\phi 30$	$\phi 31$	$\phi 30$
Bearing length B / mm	6	6	6	6	6
Reduction / %	R_{d1} =17.3	R_{d1} =16.8	R_{d2} =0.7	R_{d1} =11.8	R_{d2} =6.3
Mother bar diameter / mm	$\phi 33$	$\phi 33$		$\phi 33$	
Coefficient of friction	0.07	0.07		0.07

(a) Medium carbon steel (AISI1045)

(b) High carbon steel (AISI1110)

Fig. 11. Comparison of axial residual stress distribution by numerical and laboratory experiments.

there is an influence of work-hardening ratio on the effect of skin-pass drawing, and the effect is revealed more obviously where the work-hardening ratio is smaller.

6. DISCUSSION

As shown in Fig. 3, the work-hardening ratio has a strong influence on the axial residual stress among mechanical properties. This result implies that the intensity of residual stress may depend on flow stress, which is total of initial yield stress and work-hardening.

In Fig. 12, imaginary line 1 has the smaller yield

stress and larger hardening ratio than line 2. When the strain is enough large after drawing, flow stress of line 1 becomes larger than that of line 2. As a result, the intensity of axial residual stress of line 1 may become larger than that of line 2.

Using various pattern of stress-strain relationship in Fig. 1, comparison of flow stress after drawing σ_f and

Fig. 12. Effect of flow stress after drawing on the intensity of axial residual stress.

Fig. 13. Difference of axial residual stress between linear hardening and exponential hardening.

intensity of axial residual stress is shown in Fig. 12. The flow stress after drawing σ_f was calculated by following equations, from mechanical properties and reduction in area $R_d(\%)$.

$$\sigma_f = \sigma_e + H(\epsilon_f - \epsilon_e) \quad (2)$$

$$\epsilon_f = \ln(1 - R_d/100) \quad (3)$$

The intensity of residual stress was calculated by Eq. (1) from the analytical results shown in Fig. 3. The correlation between the flow stress σ_f and the intensity of residual stress is strong. It may be concluded that the relative intensity of residual stress will be roughly predicted from stress-strain relationship without analysis.

In Fig. 13, the analytical results of residual stresses are shown, using both linear and exponential hardening curves. As there was not a significant difference, in the present paper the linear hardening was adopted for simplicity.

7. CONCLUSIONS

(1) Investigation was carried out on the influence of material properties on the axial residual stress after cold drawing of metallic bars using both numerical and experimental approaches.

(2) Among the three factors of material properties, which are Young's modulus E , yield stress σ_e , and work-hardening ratio H , the former two have little influence on the distribution pattern of the residual stress after drawing. In other words, the magnitude of the residual stress depends on the flow stress after drawing.

(3) The distribution pattern of the axial residual stress is dependent on the work-hardening ratio. The larger H is, the larger the magnitude of residual stress is.

(4) The same conclusions apply to the skin-pass effect, which reduces the axial residual stress. It must be noted that the larger H is, the less sensitive the skin-pass effect is.

(5) There is an optimum region where the skin-pass effect is revealed most remarkably, and it lies around the point of 1.0% reduction in area on the skin-pass.

(6) The validity of these results were experimentally verified and the influences of material properties on the axial residual stress were made clear both qualitatively and quantitatively.

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