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Ductility improvement of high carbon steel by alternate wire drawing method

H. Nagashima [a,*], K. Yoshida [b]

[a] Deptartament of Graduate Student, Tokai University 4-1-1 Kitakaname, Hiratsuka, Kanagawa, Japan

[b] Deptartament of Precision Engineering, School of Engineering, Tokai University

* Corresponding e-mail address:5bmkm056@mail.u-tokai.ac.jp

ABSTRACT

Purpose: High carbon steel wires have been widely used in industrial products such as bridge cables and steel cords for automotive tires due to their high mechanical strength and high fatigue characteristics. The wires are expected to have higher strength and smaller diameter in the future. Wire drawing is carried out to measure up to these requirements. However, after the processing, tensile strength increases, but ductility decreases due to the shear deformation on the wire surface. This research focuses on increasing the ductility for high carbon steel wires for production.

Design/methodology/approach: As a process for obtaining wires with high strength, high ductility, and high fatigue strength, “alternate drawing” is proposed. Alternate drawing is a wire drawing process where the direction of the material flow is changed every few passes.

Findings: And tensile test, torsion test, FEM analysis, and bending test were carried out to investigate the effect on alternate drawing on the ductility of the drawn wire. And then the results were compared with those of wires processed by conventional drawing. It is revealed that mechanical properties of wires processed by alternate drawing have been improved by the decrease of additional shear- strain accumulation on the wire surface portion.

Research limitations/implications: This research is focused on the improvement of ductility, so in it the future we hope to achieve even lower drawing diameters and make finer wires.

Practical implications: These fine high carbon steel wires could be used for making steel cord for vehicle tires, production of springs and production of steel ropes for industrial purposes.

Originality/value: This paper is based on a previous research from Tokai University’s Yoshida Laboratory, but all the experiments and results were conducted by me.

Keywords: Ductility; High carbon steel wire; Alternate wire drawing; Delamination

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PROPERTIES

1. Introduction

Recently high carbon steel wires that have high-strength has been used extensively for bridge cables, steel cords for tires and PC steel wire. Therefore, the practical application of high carbon steel needs high-strength and high-ductility when manufactured by using wire drawing. Also if high carbon steel wire had higher strength and smaller diameter, it could be used for making smaller and lighter products.

However, high carbon steel has problems with ductility. The high carbon steel wire has decreased ductility when there is high.

concentration of carbon and increase in delamination. High carbon steel ductility is decided by torsion test. The high ductility wire is breaking perpendicular to the drawing direction, as in low ductility wire's case vertical cracks occur along the drawing direction [1,2], which are caused by decrease in ductility. Thus it is difficult maintain high strength and ductility.

This study is intended to improve ductility and delamination suppression of high carbon steel drawn wire, we propose an alternating wire drawing as a solution. Conventional wire drawing is deformed by compressive stress and relatively simple tensile stress, but near the wire surface additional shearing stress is accumulated. The additional shearing deformation that will become shearing strain would be accumulated significantly from work hardening. Therefore, the strength increases but the ductility decreases proportionally. However, we can expect ductility improvement, for it is possible to suppress the additional shear deformation in the wire surface area by changing the drawing direction at every pass with alternating wire drawing. The alternate wire drawing methods are shown in Figure 1. In fact, it is possible to receive high ductility in the evaluation of pure aluminum, which is a non-ferrous metal [3,4].

Alternate drawing process works by not allowing significant increase of additional shearing strain to the metal surface, the opposite of most processing methods, such as ECAP (Equal Channel Angular Pressing) method. ECAP method is used to get ultra-fine metal grain that has a higher workability. This happens by extruding the material repeatedly using bent dies with an equal diameter [5]. The principle of ECAP method is shown in Figure 2 [6]. Its purpose is to improve the mechanical properties of the material, the additionally in wire drawing, it is intended to improve the mechanical properties by suppressing the shearing strain.

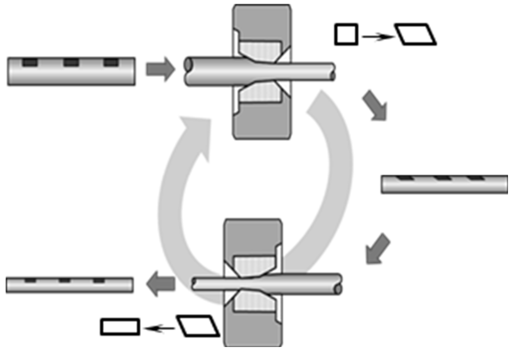


Fig. 1. Alternate wire drawing process

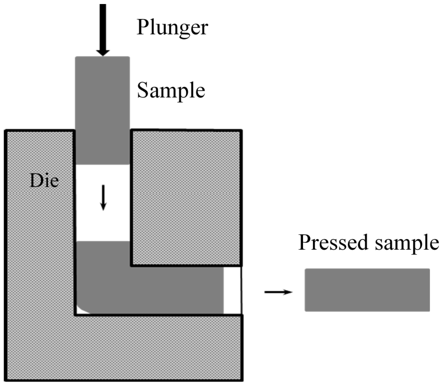


Fig. 2. Equal-channel angular pressing method

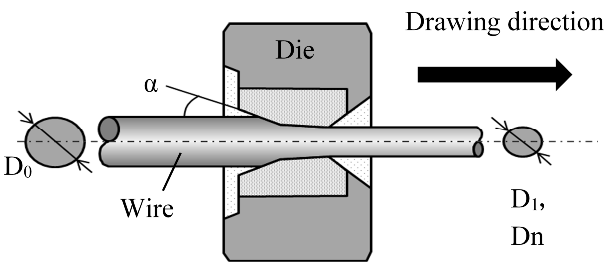
2. Experimental method

2.1. Drawing process

In this study, the used material is high carbon steel (SWRS82A) wire with a diameter of 4.5 mm. Chemical composition of SWRS82A is shown in Table 1. Reduction per pass (R/P) in the wire drawing was about 20% and the total reduction (*Rt*), was 91.7%. The explanation of reduction per pass (R/P) and total reduction (*Rt*) is shown in Figure 3 [7], also equation (1), (2). The drawing speed was 500mm/min. Tungsten carbide dies with a half angle of 6° and lubricant LS50N were used on for the drawing.

Table 1.
Chemical composition of SWRS82A (%)

	C	Si	Mn
SWRS82A	0.82	0.18	0.48
	P	S	Cu
	0.009	0.008	0.01



$$R/P = \left[1 - \left(\frac{D_1}{D_0}\right)^2\right] \times 100[\%] \quad (1)$$

$$R_t = \left[1 - \left(\frac{D_n}{D_0}\right)^2\right] \times 100[\%] \quad (2)$$

Fig. 3. Definition of wire drawing

Wires with a Rt=91.7% (total pass number is 11 passes) which used alternate drawing in every pass, every 3 passes and 5 passes are shown in Figure 4 and conventional drawn wires with the same number of passes as that of alternate drawn wires were prepared to check the usefulness of the proposed method. After that the strength and ductility of each wire was compared by conducting tensile strength test.

2.2. FEM analysis of wire drawing

The effectiveness of alternate drawing in which the drawing direction is reversed for each pass, was verified by evaluating the mechanical properties, hardness distribution, and equivalent strain of drawn wires obtained by FEM analysis. Conditions of the FEM analysis are shown in Table 2.

Table 2.
Material and friction condition for FEM

Young's modulus E[GPa]	206
Poisson's ratio γ	0.312
Work-hardening exponent	σ=4808$\varepsilon^{0.59}$
Coefficient of friction μ	0.05

3. Results and discussions

3.1. Results of tensile strength test

Hereafter, W_1 represents the wire processed by alternate drawing with change of direction for every pass, W_3 and W_5 wire's case the change in direction is every 3 and 5 passes accordingly and Wc wire is processed by conventional drawing. Figure 5 shows stress-strain curves obtained from the tests and also Vickers hardness test for each wire is shown in Figure 6.

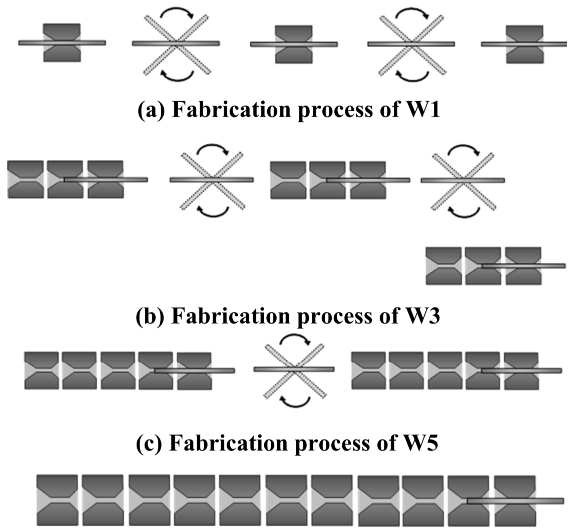


Fig.4 Fabrication process of several drawn wire

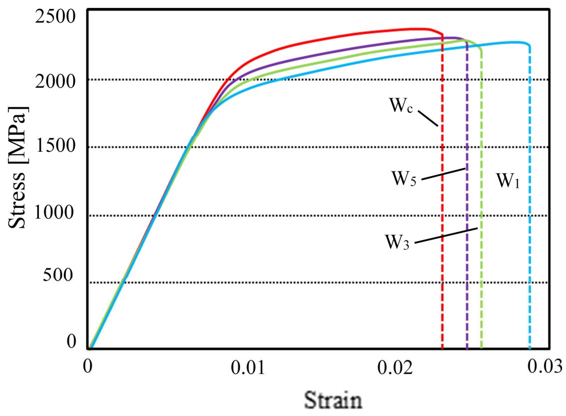


Fig. 5 Stress strain curves of several drawn wire (91.7%)

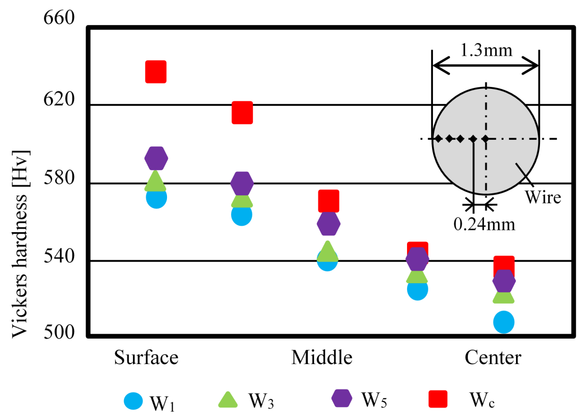


Fig.6 Vickers hardness of several drawn wire (91.7%)

It can be seen that tensile strength of W_1, W_3 and W_5 are lower than that of a conventional drawn wire, also the value of breaking strain of W_1, W_3 and W_5 is higher than that of the conventional drawn wire. The value of the breaking strain of Wc is 0.0233, as the alternate drawn wire W_1 is 0.0287, W_3 is 0.0254, W_5 is 0.0249., this means that ductility of the alternate drawn wire has improved compared to the conventionally drawn wire.

3.2. Prediction of accumulated shearing strain by FEM analysis

In this analysis, to verify that the alternating wire drawing suppresses accumulation of additional shearing strain, the drawn wire was subjected to a FEM analysis of conventional and alternating wire drawing of high carbon steel wire. In addition, this analysis was carried out with drawing analysis of up to a total reduction rate Rt=91.7% (11 pass) in each processing method.

As shown in Figure 7 in case of wire drawing process, the flow of the material receives the additional shear deformation near the surface on wire due to contact with the die. However inside of the wire is subjected to only simple tensile deformation and compressive deformation. Therefore, the centre of the wire moves faster than the surface layer portion. In addition, Figure 8 shows alternating wire drawing and change of element shape of the wire surface portion of each of the processes done by FEM.

From the FEM results, we can confirm that for the conventional drawn the element shape of the wire surface layer portion of Rt=36% (2pass) has changed significantly. Then, when Rt reaches 91.7% (11pass), the element shape of the wire surface portion is largely deformed. Therefore, as the wire was drawn in a single direction, additional shear deformation continues, it can be assumed that additional shearing strain increases.

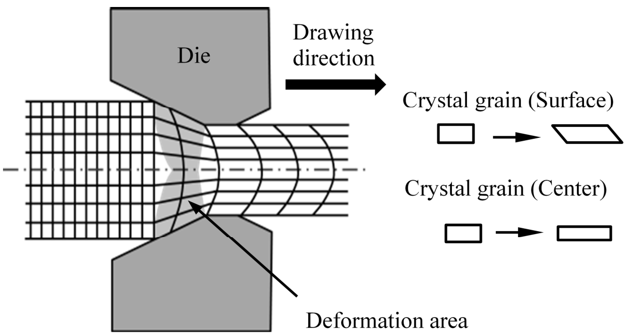


Fig.7. Change of the crystal grain

On the other hand, in the case of the alternate drawn wire, we can confirm that at Rt=91.7% (11pass), the metallic grain has a near rectangular shape. From this result, it can be speculated that alternate drawing can suppress the increase of additional shear strain.

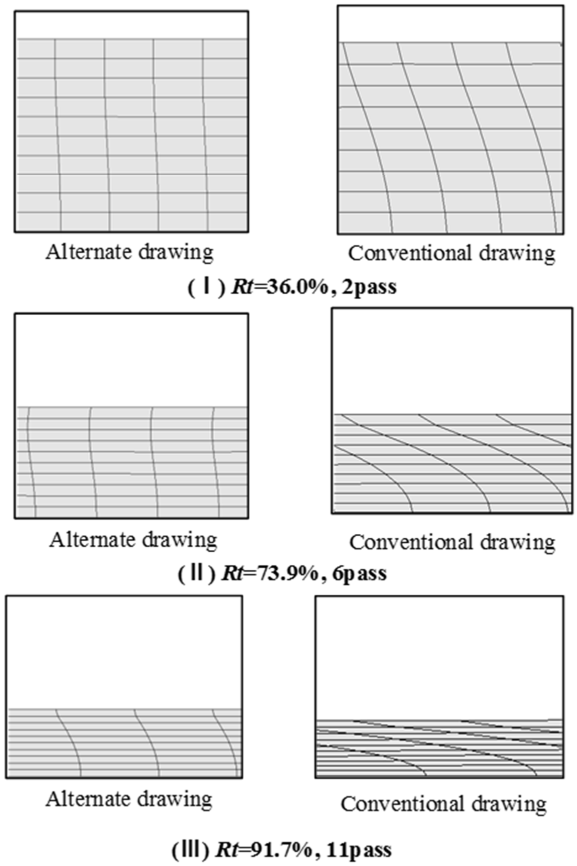


Fig. 8.Transition of element deformation with increasing of Rp by FEM

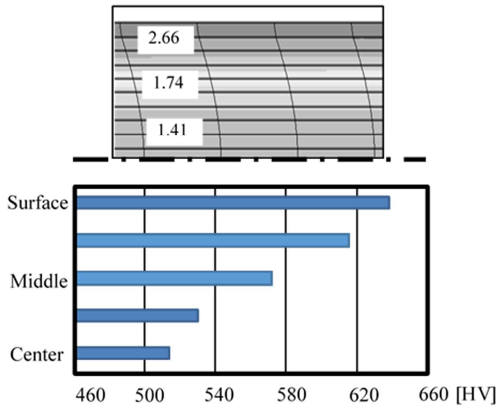


Fig. 9. Relationship of equivalent strain and Vickers hardness by conventional drawing (Rt=91.7%)

In addition, the equivalent strain and relationship of Vickers hardness of each processing method obtained in this analysis is shown in Figure 9 and Figure 10 accordingly. The measurement points for the Vickers hardness test have the same distance in between and start from the surface to the centre.

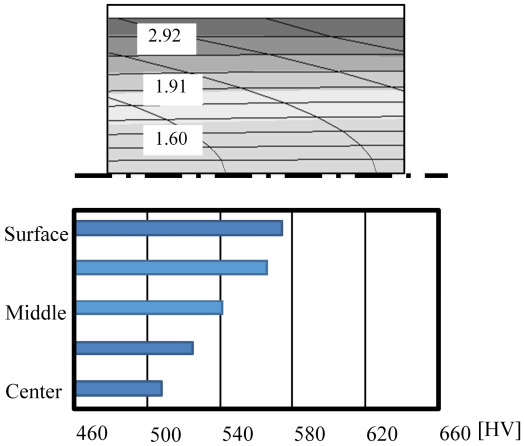


Fig. 10. Relationship of equivalent strain and Vickers hardness by alternate drawing (Rt=91.7%)

From these results, we can confirm that the equivalent strain of the wire has a smaller value than the one-way drawn material in alternating drawing material's case.

We can conclude that with alternating wire drawing we can suppress shearing strain increase more than the conventional wire drawing method, due to the smaller deformation of the metallic grain near the surface.

Also, it can be seen in Figure 9 and Figure 10 that the value of the Vickers hardness increases with the higher number of equivalent plastic strain. Also, the difference between the Vickers hardness near the centre and near the surface is much smaller in the case of the alternate drawing method compared to that of the conventionally drawn wires. With this, we can state that if we can decrease the total equivalent strain of the material we can also decrease the work hardening near the surface. Also, it can be said that the equivalent strain and hardness is correlated.

3.3. Torsion test of the drawn wires

The wires were subjected to torsion test to investigate the presence or absence of torsion characteristics and the increase or decrease of delamination for small diameter drawn wire by the discussed methods.

In this test, the torsion speed is set to 1080 degree/ min, a chuck distance was set to 100*d [8] as is JIS standard . Therefore, since the drawing material used in this test has a diameter of 1.3 mm, the chuck distance is set to 130 mm. In this study, the image of each torsion thin wire obtained is shown cross-sectional point of view.

Figure 11, 12 are SEM images of the breaking wire surface in the torsion test of the conventional and alternate drawn wire. The conventional drawn wire appeared to have delamination marked with vertical cracks along the drawing direction, in the alternate drawing material, it was confirmed a vertical fracture surface is in the drawing direction.

Due to these observations, the conventional drawn wire is considered to have high difference of additional shearing strain at the surface layer portion and the center portion. Additional shear deformation in the surface layer portion is increased, thus additional shearing strain is significantly accumulated and it can be assumed that the extreme work hardening led to delamination that occurred in the vicinity of the surface layer portion. With the alternately drawn wire's small additional shear deformation of the surface layer portion and the center portion, it is possible to suppress additional shearing strain, also it has led to the suppression of delamination due to reduction of the work hardening.

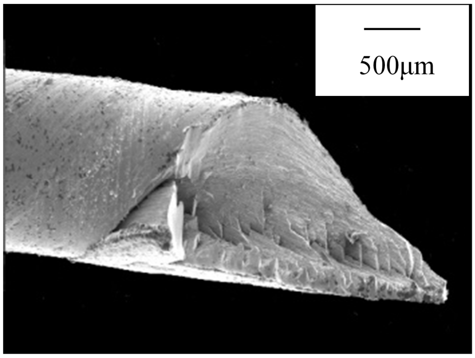


Fig. 11. SEM image of breaking surface of Conventional drawn wire in torsion test

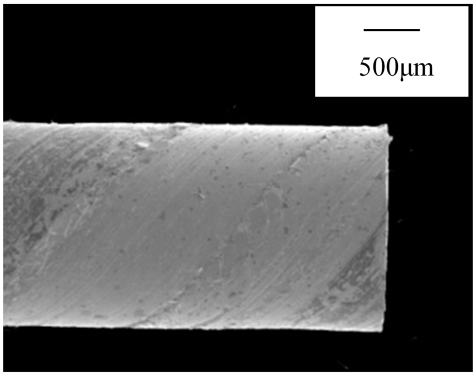


Fig. 12. SEM image of breaking surface of Alternate drawn wire by torsion test

3.4. Bending characteristics of the wires

To investigate the bending characteristics, each drawn wire was subjected to bending test for the finishing wires (Rt=91.7%) of each process. The SEM image of a conventional drawn wire obtained in this study is in Figure 14 also the SEM image of alternate drawn wire is in Figure 15.

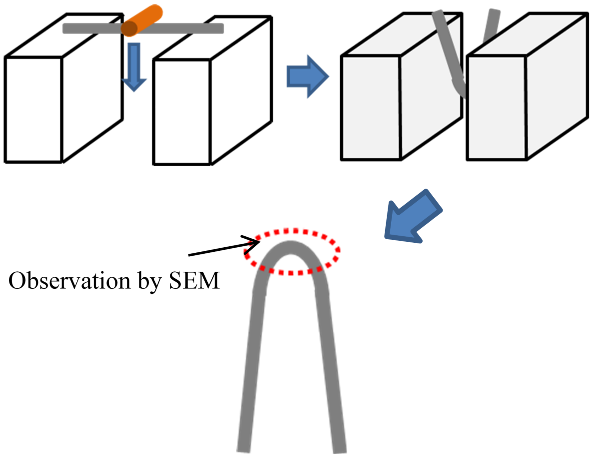
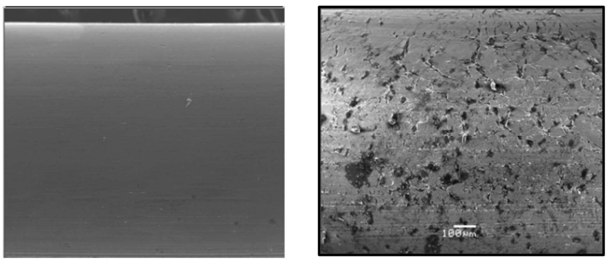
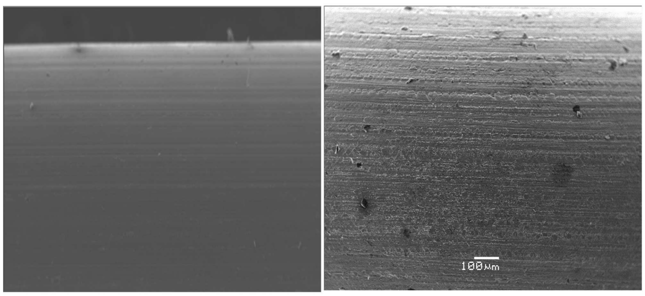


Fig.13 Bending test method



a) Before bending test **b) After bending test**

Fig. 14. SEM images of wire surface of conventional drawn wire before and after bending test



a) Before bending test **b) After bending test**

Fig. 15. SEM images of wire surface of alternate drawn wire before and after bending test

In the case of the conventional drawn wire, the bending test shows cracks at the wire surface part. However, in the alternate drawing material, it was possible to maintain a good surface after being subjected to the bending test. Following these results, we can conclude that in the case of the conventionally drawn wire the increase of shearing strain near the surface makes it difficult to preserve a good surface quality after bending, as in the case of the alternate drawn wire, the surface remains in good condition.

4. Conclusions

Using wires which were processed by alternate drawing in every pass, every 3 passes, and every 5 passes and drawn up to Rt=91.7% (total pass number is 11 passes) their mechanical properties, prediction of accumulated shearing strain by FEM, torsion test, and bending test were compared with conventional drawn wires with the same Rt. The results are as follows:

1) Wires processed by alternate drawing in every pass showed the highest ductility, also wires processed by alternate drawing every 3 passes and 5 passes showed relatively high ductility.

2) In FEM analysis, alternate drawing method resulted in inhibition of total equivalent plastic strain and Vickers hardness at the wire surface.

3) From the torsion test, in the conventional drawn wires' case delamination occurred. However the alternate drawn method prevented the delamination, which led to the breaking in a vertical direction.

4) From bending test, the conventional drawn wire resulted in the formation of cracks in the wire surface portion, as for the alternating drawn wire, it was able to maintain a good surface without cracks, that was possible due to the retained ductility of the wire surface layer part.

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Additional information

Selected issues related to this paper are planned to be presented at the 22nd Winter International Scientific Conference on Achievements in Mechanical and Materials Engineering Winter-AMME'2015 in the framework of the Bidisciplinary Occasional Scientific Session BOSS'2015 celebrating the 10th anniversary of the foundation of the Association of Computational Materials Science and Surface Engineering and the World Academy of Materials and Manufacturing Engineering and of the foundation of the Worldwide Journal of Achievements in Materials and Manufacturing Engineering.

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