

# Grain Coarsening Resistance of Low-Carbon Drawn Wire during the Annealing Process

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Low-carbon steel wires are widely used for fasteners, such as screws, rivets, and nuts. A drawing process prior to annealing is commonly applied for accurate diameter in order to be cold headed precisely with ease. Nevertheless, the above process tends to cause abnormal grain growth if the manufacturing process of steel wire is not properly controlled. It is well known that initial grain size is a key factor to affect the nuclei of recrystallization and precipitates have the benefit to inhibit the grain growth. This research shows that finishing rolling temperature is crucial for obtaining uniform ferrite grain prior to drawing and cooling control after rolling can induce the precipitation of AlN. According to the adjusted manufacturing process of low-carbon steel wire, abnormal grain growth can be effectively prevented for the drawn wire subjected to annealing treatment.

**Keywords:** Annealing, Abnormal Grain Growth, AlN, Drawing, Low-carbon Steel Wire

## 1. INTRODUCTION

Low-carbon steel wires are widely used for fasteners, such as screws, rivets, and nuts. A drawing process prior to annealing is commonly applied for accurate diameter in order to be cold headed precisely with ease. Abnormal grain growth sometimes happened in a drawn wire when subjected to annealing treatment, while this was not always the case, such unpredictable situations would bothered the manufacturer. For solving the above problem, it is crucial to prevent the grain from abnormal growth by adjusting the manufacturing process of the low-carbon steel wire.

It is well known that cold-worked metals are able to store strain energy associated with various lattice defects by the plastic deformation. These stored energies elevated the free energies of cold-worked metals and made the deformed metals unstable. These unstable deformed metals may soften spontaneously, and the softening rates can greatly speed up by heating these deformed metals. The annealing process is widely used to soften these cold-formed steels by heating them to below Ac1 temperature. During the annealing process, there are three well known processes (i.e., recovery, recrystallization and grain growth) that take place in succession. Recovery and recrystallization are caused by the release of strain energy. Finally, grain growth occurs by lowering the surface energy.

For solving the abnormal grain growth of a drawn

wire subjected to annealing treatment, it is better to know in advance what factors will affect recovery, recrystallization and grain growth, respectively. The factors affecting recovery is omitted to discuss, while some factors affecting recrystallization and grain growth will be considered in this research. According to possible influence factors, we were able to put the prevention of abnormal grain growth into practice.

There are several factors affecting recrystallization, such as temperature, strain, heating rate, purity of the metal, initial grain. The factors affecting grain growth might include impurity atoms in solid solution, impurities in the form of inclusions, the free-surface effects and preferred orientation. There are so many factors affecting recrystallization and grain growth regarding the above mentioned. Which factor would be the key determinants were hard to find out. Therefore, how to solve this problem was very tricky at the beginning. In the end, several important impact factors were summarized, and countermeasures were made for inhibiting the abnormal grain growth against these factors.

## 2. EXPERIMENTAL METHOD

### 2.1 Materials

Abnormal grain growth is occasionally observed within low-carbon drawn wires subjected to annealing treatment. These low carbon steels may include different steel grades such as 1003, 1006, 1008, and 1010. Only

the steel wire 1006AK is used for this study. It is a typical common low-carbon steel with 0.03%~0.07% carbon content, and it is deoxidized with aluminum to reduced the oxygen content. The aluminum content is about 0.025%~0.06% and the nitrogen content is about 30~65 ppm. Two different diameter wires ( $\phi$  5.5mm &  $\phi$  6.5mm) were arbitrarily utilized for trials in this research.

## 2.2 Drawing

According to the manufacturer's ordinary process, the drawing ratio is about 30~40%. Although increasing the drawing ratio is beneficial for obtaining more fine grains by formation of more recrystallization nuclei during the annealing treatment, the manufacturer was not willing to adopt this method in order to avoid increasing of the drawing process or damaging the drawing dies. Two different drawing ratios (36% & 37%) of low-carbon drawn wires were arbitrarily chosen prior to annealing treatment in this research. The drawing passes are listed below.

$\phi$  5.5mm  $\rightarrow$   $\phi$  4.6mm (30%)  $\rightarrow$   $\phi$  4.35mm (37%)

or

$\phi$  6.5mm  $\rightarrow$   $\phi$  5.5mm (28%)  $\rightarrow$   $\phi$  5.2mm (36%)

## 2.3 Annealing Treatment

The conditions of the annealing treatment were mainly set at 670°C for 6~8 hours. The annealing treatment carried out either by the in-lab furnace or on the production line must be taken into account as the ability of the heating rate between these two kinds of furnaces vary. The heating rate of the production line is much slower due to the huge volume of the furnace. Therefore, the heating rate of the in-lab furnace should be set as close as possible to that in the production line. The heating rate in the production line is about 0.03°C/s.

## 2.4 Morphology Observation

The morphologies of grain were observed by Leica AG CH-9435 Heerbrugg optical microscopy at different magnifications.

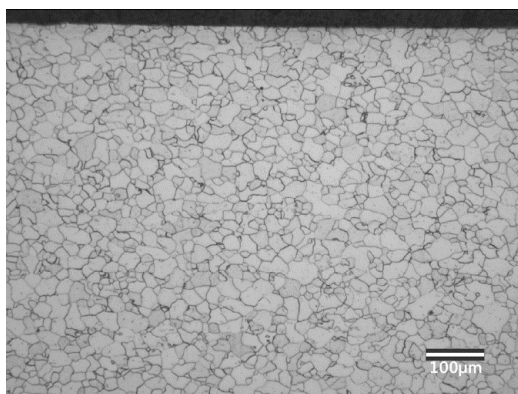
## 2.5 Transformation Temperature of Ar3

Ar3 is a transformation temperature varied with different compositions, prior austenite grain sizes and cooling rates at which part of  $\gamma$  phases are beginning to turn into  $\alpha$  phases. From Fe-C binary phase diagram, low carbon steel possesses a relatively high A3 temperature which is close to the finishing rolling temperature set by steel wire/rod mills. It implies that the finishing rolling temperature may be in a single-phase region ( $\gamma$ ) or a two-phase region ( $\alpha + \gamma$ ), which will cause the ferrite grains to have different energy states. As a result, which finishing rolling temperature to be set at is quite important in affecting the morphology of ferrite grains. Several Ar3 temperatures of different 1006AK steel wires were obtained by using a dilatometer.

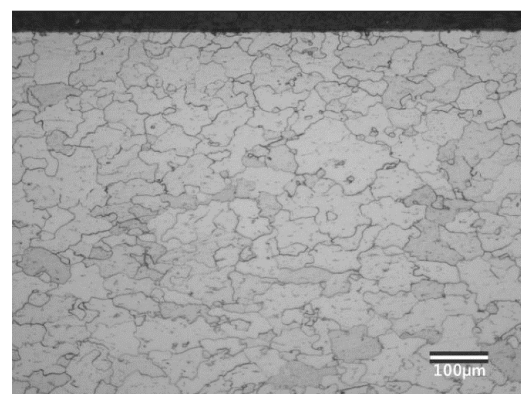
# 3. RESULTS AND DISCUSSION

## 1. INTRODUCTION

Figure 1(a) and 1(b) show the morphologies of ferrite grain for two different sections of the 1006AK drawn wire subjected to 670°C/6hrs annealing. These two sections were cut off arbitrarily from the same annealing-treated drawn wire, but they showed quite distinct morphologies of grain on these two images. In practical production, abnormal grain growth sometimes happened, while that was not always the case. It still bothered the manufacturer with the so-called "spangles" caused by coarsening grains that appeared on the surface of a steel wire. Because spangles were unpredictably occurring at times, several improvements will be suggested as follows.



(a)



(b)

**Fig.1.** Two different sections of the 1006AK drawn wire subjected to 670°C/6hrs of annealing.

Figure 2(a) and 2(b) show the morphologies of ferrite grain cut off arbitrarily from the same as-rolled wire. In practical cases, it was easily found that the distribution of grain size was rather wide and uneven within the surface of many different as-rolled 1006AK wires, while that was fairly uniform within the center of the matrix. Such an interesting phenomenon manifested in the distribution of grains are shown in figure 3(a) and 3(b).

The reason why the grains on the surface of the steel wire were relatively easy to be coarse was suspected to be related to the finishing rolling temperature. The Ar3 transformation temperatures ( $\gamma \rightarrow \alpha + \gamma$ ) for several

different composition 1006AK wires were measured in the range of about 845°C~875°C. This temperature range is quite close to the finishing rolling temperature set by the previous manufacturing process. Figure 4a and figure 4b show the thermomechanical simulations for the finishing temperature of 1006AK steels at two different temperatures and two different cooling rates after the finishing rolling process. The simulating temperature of finishing rolling shown in figure 4a is within a single-phase region ( $\gamma$  phase), while that in figure 4b is within a two-phase region ( $\alpha + \gamma$  phases).

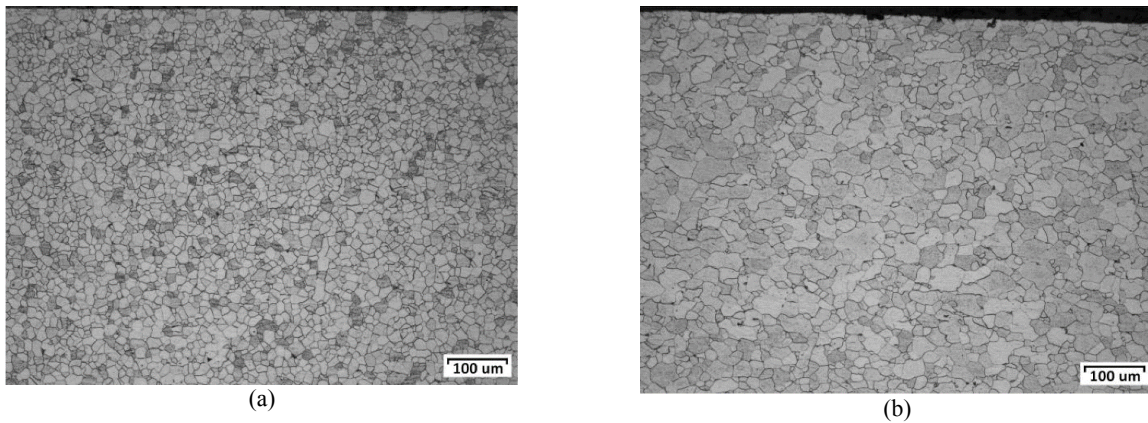


Fig.2. Two different sections of the 1006AK as-rolled wire.

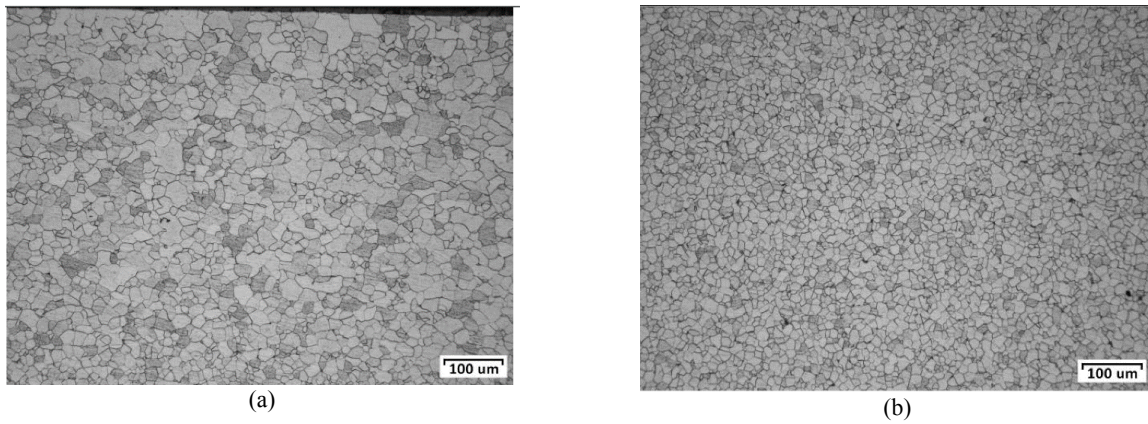


Fig.3. OM images of 1006AK as-rolled wire observed on a) surface b) core.

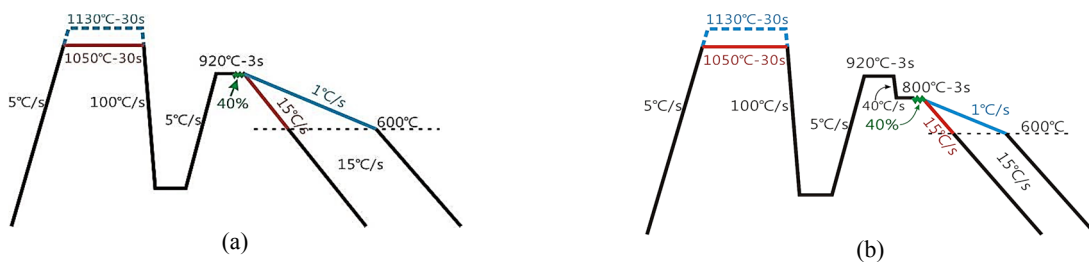
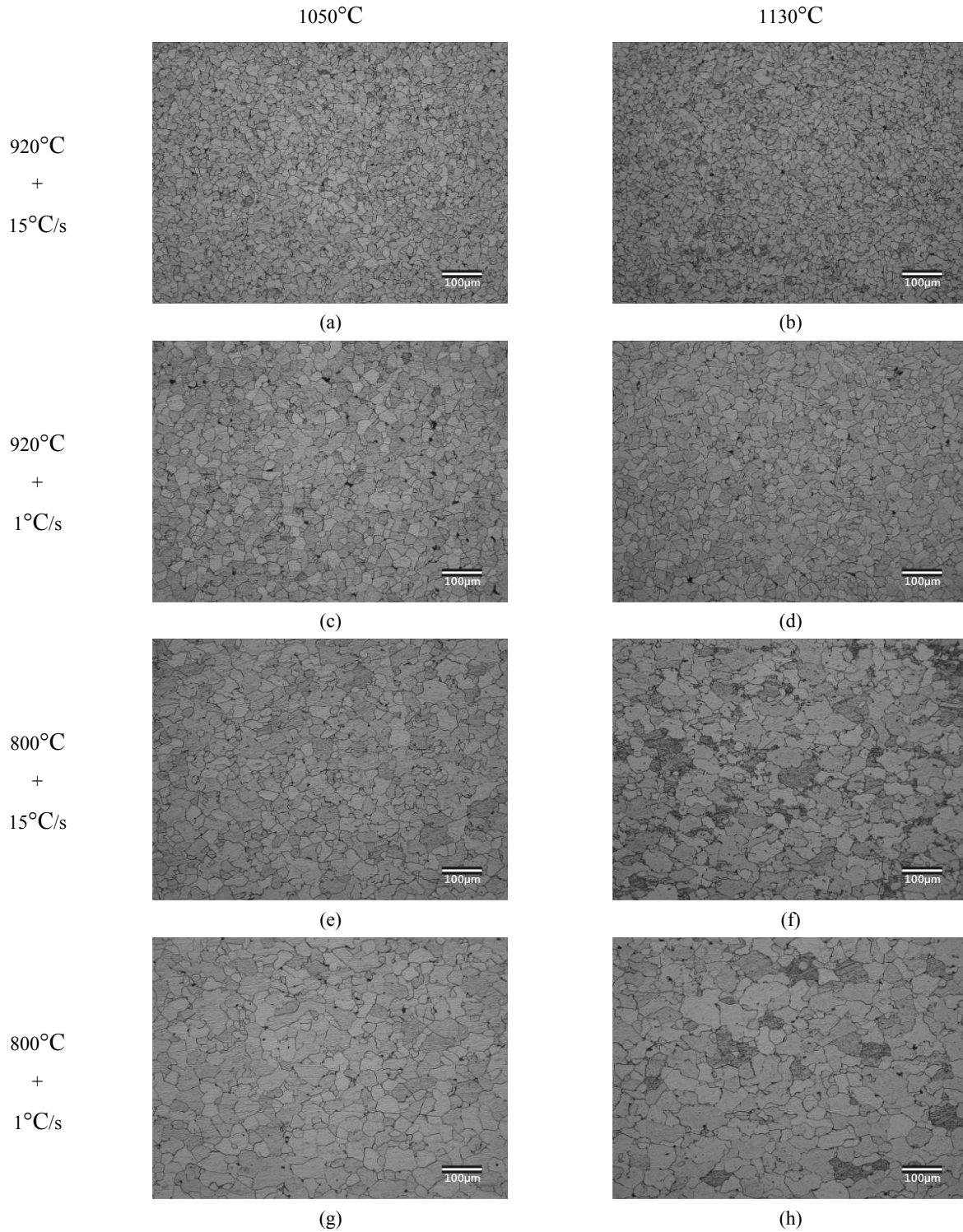


Fig.4. Different thermomechanical simulations for the finishing rolling of 1006AK steels within (a) a single-phase region (b) a two-phase region.

Figure 5(a)~5(h) show the different morphologies for the 1006AK steels by different thermomechanical simulations according to figure 4. It reveals that a finishing rolling temperature set within a single-phase region ( $\sim 920^{\circ}\text{C}$ ) is beneficial for obtaining equiaxed ferrite

grains, while abnormal ferrite grains are obviously found by the simulation of a finishing rolling temperature set within a two-phase region. In order to verify the effect of the finishing rolling temperature on the initial grain of ferrite, two different finishing rolling temperatures were



**Fig.5.** Different morphologies for the 1006AK steels by different thermomechanical simulations according to figure 4..

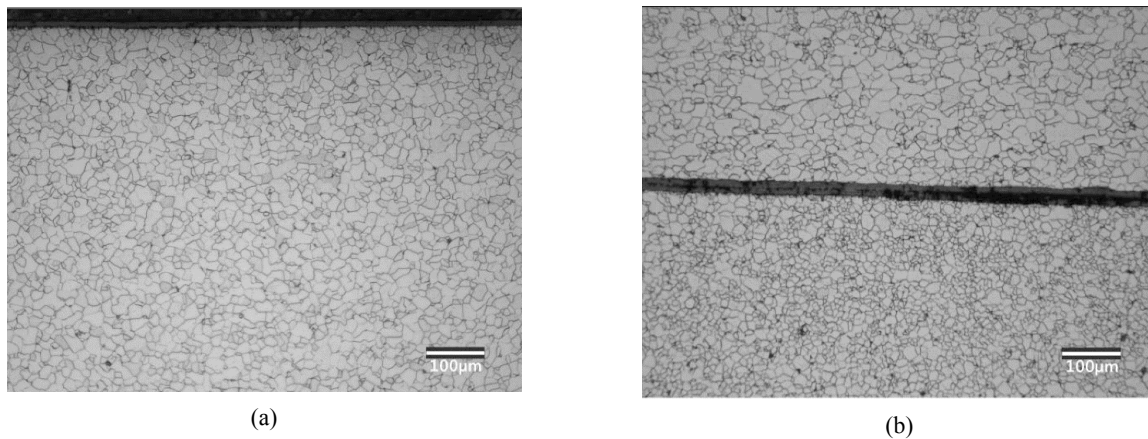
carried out in the production line. Figure 6(a) and 6(b) show the OM images for the 1006AK steels subjected to the two finishing rolling temperatures within a single-phase region and a two-phase region respectively. It reveals that a finishing rolling temperature set within a single-phase region is beneficial for obtaining uniform equiaxed ferrite grains as shown in figure 6(a), while the unevenness and wide size distribution of ferrite grains are shown in figure 6(b) for the simulating finishing temperature set within a two-phase region.

Although the morphology of the initial grain as shown in figure 7(a) had been improved according to the rolling parameter adjustment, abnormal grain coarsening as shown in figure 7(b) still had been found within this drawn wire (37%:  $\phi 5.5 \rightarrow \phi 4.35$ ) subjected to an annealing treatment (670°C/6hrs). The results show that the abnormal grain growth after annealing can not be effectively suppressed only by improving the initial grain. There should be other factors that can be utilized to suppress grain growth.

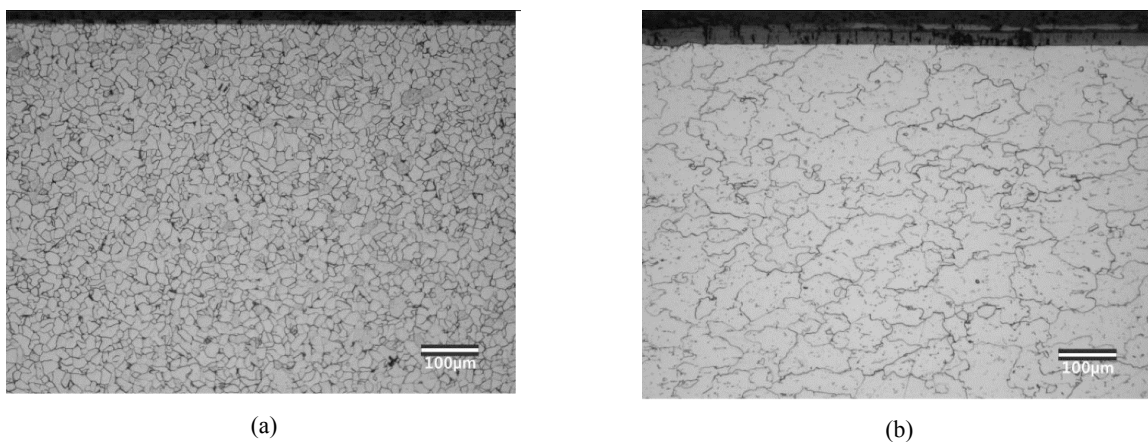
It is well known that precipitates can inhibit the

migration of grain boundary and prevent grain growth. Hence, how to introduce the precipitates precipitating without adding other precipitation elements is crucial. 1006AK steel wire is an Aluminum-killed steel, the AlN precipitates are most likely to have the opportunity to suppress grain boundary migration. According to the AlN precipitation controlling technology carried out by rolling the 1006Ak steel wire, the TEM images by replica for the 1006AK steel wire are shown in figure 8. In addition to observing a MnS inclusion in figure 8a, it is very hard to find AlN precipitates for the specimen without AlN precipitation controlling, while several AlN precipitates for the specimen by AlN precipitation controlling has been found in the replica-prepared film shown in figure 8(b).

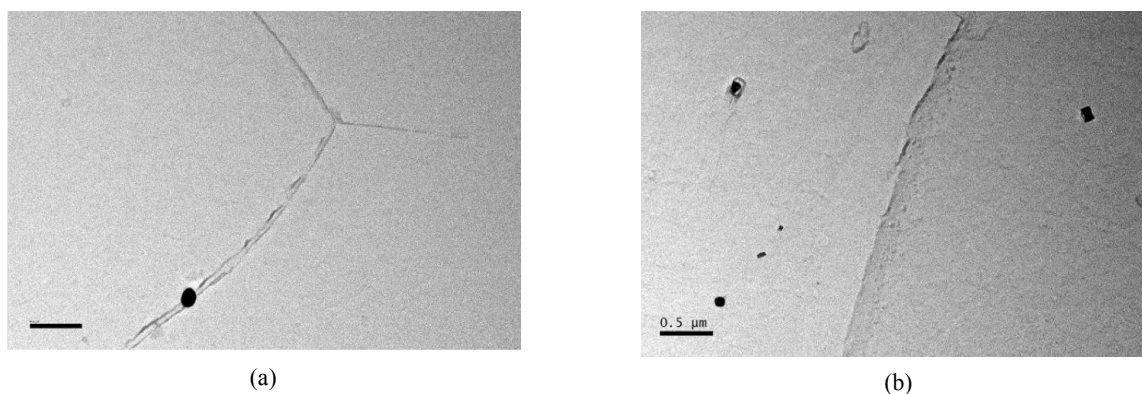
Not only were the initial grains improved, but also the AlN precipitates were introduced for the 1006AK steel wire by modifying the manufacturing process. The morphology of initial grain for the as-rolled steel wire was shown in figure 9a, and no serious abnormal grain growth had been found in figure 9b within the drawn



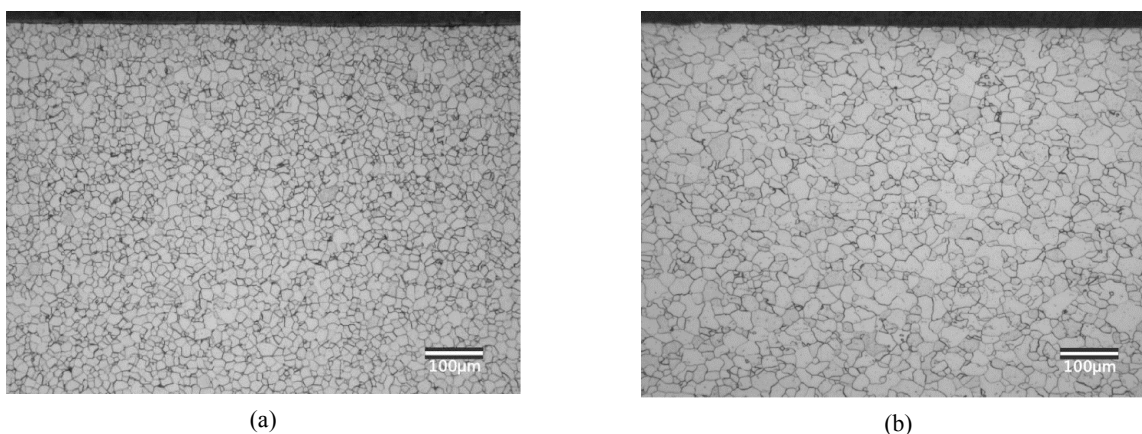
**Fig.6.** The finishing rolling temperatures were set within the (a)  $\gamma$  region and (b)  $\alpha+\gamma$  region



**Fig.7.** The morphologies of grain (a) prior to annealing (b) subjected to drawing & annealing for the 1006AK steel wires without AlN precipitation controlling.



**Fig.8.** The TEM images by replica for the 1006AK steel wire (a) without AlN precipitation controlling (b) with AlN precipitation controlling.



**Fig.9.** The morphologies of grain (a) prior annealing (b) subjected to drawing & annealing for the 1006AK steel wires by AlN precipitation controlling.

wire (36%:  $\phi$  6.5  $\rightarrow$   $\phi$  5.2) subjected to an annealing treatment (670°C/6hrs). The results show that the abnormal grain growth can be effectively suppressed by integration of the initial grain improvement and the introduction of precipitates.

#### 4. CONCLUSIONS

Abnormal grain growth had occasionally been found within the low-carbon drawn steel wire subjected to an annealing treatment before the improvement of adjusting the manufacturing process. There often existed a wide distribution of non-uniform grain size in the matrix of as hot-rolled wire and no AlN precipitation controlling was introduced during the manufacturing process for 1006AK steel wire. These two adverse factors will help the formation of abnormal grain growth. The distribution of a more uniform initial grain can be obtained by rolling control within a single-phase rolling, while the grain boundary migration can be inhibited by AlN precipitation control. As a result, abnormal grain growth

can be effectively prevented by the uniform initial grain distribution and AlN precipitates simultaneously.

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