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Static Strain Aging Behavior of Low Carbon Steel Drawn Wire

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Abstract: The static strain aging behavior of low carbon steel wires after drawing process is studied. To do so, the wires are austenitized at different temperatures and cooled in different rates. Then the wires are drawn and aged at a specific temperature and time. Before and after aging of each drawn wire, the hardness distribution at its cross section is measured. The increase in hardness due to aging is called aging index. The results show that the hardness of drawn wire is increased from center to surface of its cross section. However, after aging the hardness is decreased from center to surface. In addition, with increasing the austenitizing temperature, the index is increased. Also, with increasing the cooling rate, the index is decreased. Moreover, the aging index is decreased from center to surface.

Keywords: Static strain aging, wire drawing, austenitizing temperature, cooling rate, hardness

1. Introduction

Strain aging is a phenomenon that occurs in low carbon steels at a specific temperature and time after straining called static strain aging or through straining called dynamic strain aging [1]. This phenomenon increases the flow stress and decreases the ductility, significantly. The ductility of wire is very important in industrial lines of wire drawing. Since, the low carbon steel wires are the product of hot rolling process, the process parameters have a significant effect on the mechanical properties of the wires. Two important parameters are the finish rolling temperature that the wires cool from this temperature to room temperature and the cooling rate. The higher finish rolling temperature leads to the austenite grain growth and thus the coarser ferrite grain size is achieved [2]. Also, the higher cooling rate causes to transformation temperature reduction and finally the finer ferrite grain size due to higher nucleation rate is obtained [2].

Solute carbon and nitrogen have the main role on the strain aging of low carbon steels [1]. Since the finish rolling temperature and the cooling rate determine the solubility of carbon and nitrogen [1,3], they are the important parameters which influence the strain aging behavior of the low carbon steel wires produced by hot rolling process. Moreover, the mentioned parameters can affect on the strain aging by increasing or decreasing the grain boundaries which are the diffusion path of solute elements through the material [2].

It has been reported that during industrial wire drawing process, the temperature is increased to 200 °C [4] and between the die stands, the time of 1 min is available which are sufficient for the static strain aging occurrence [3]. Moreover, by using tensile test, it has been found that the static strain aging and multi stage strain aging can decrease the ductility of low carbon steels, significantly [1,3]. In other words, the specimens with higher solute elements have the higher strain aging sensitivity, i.e. higher increase in flow stress and decrease in ductility.

The effects of finish rolling temperature and cooling rate of the wires on their static strain aging behavior after real strain path of wire drawing as the prestrain for strain aging occurrence have not yet been investigated. However, there are some works on static strain aging behaviors using the tensile

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prestrain imposed by tensile test [1, 3, 5]. As shown in Fig. 1, Rashid [5] has found that in strain aging of different steels, with increasing the prestrain, the increase in flow stress is increased and after a specific prestrain value, the increase in flow stress is decreased.

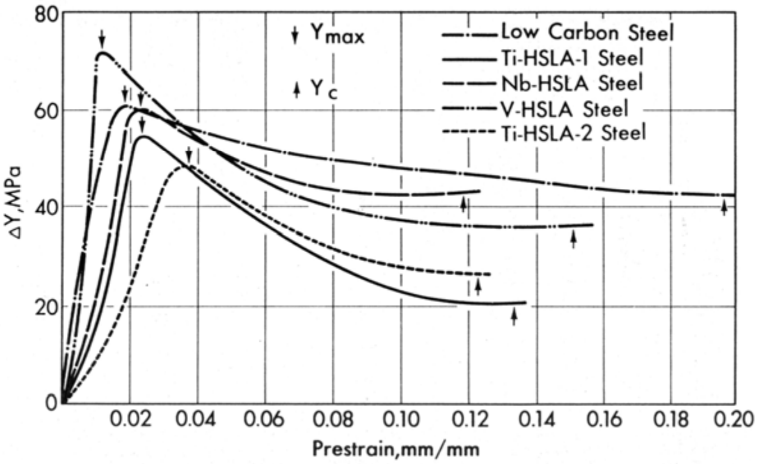

Fig. 1. The effect of prestrain on yield stress increase due to aging [5].

In this study, in order to find the real behavior of drawn wire after static strain aging, the wire drawing process is carried out on the wires to have prestrain with real strain path of wire drawing. In laboratory scale, different austenitizing temperatures regarded as different finish rolling temperatures and different cooling rates are applied on the wires. The wires are drawn then and strain aged statically. To assess the strain aging sensitivity of the wires, the hardness distributions at the cross sections of the wires are measured and compared with that before strain aging.

2. Experimental procedure

In this study, a low carbon steel wire of 3.5 mm diameter was used. The chemical composition of the wires is shown in Table 1.

Table 1. Chemical composition of studied low carbon steel

Element	C	Si	Mn	S	P	N
Weight percent	0.07	0.02	0.45	0.012	0.017	0.0026

The specimens were austenitized at different temperatures of 850 °C, 950 °C and 1050 °C for 20 min. These specimens were cooled at different rates, i.e. by fan, in air and in furnace. Then the specimens were drawn through a wire drawing die with the semi angle of 30° and the reduction in area of 25%. The prestrained specimens by the wire drawing process were aged at an oil bath of 200 °C for 1 min and then they were quenched at water. For investigating the strain aging behavior and the effects of austenitizing temperature and cooling rate, the Vickers microhardness measurement was performed at the cross section of specimens before and after aging. In other word, the microhardness distribution at the cross section of the wires was achieved.

3. Results and Discussion

Figure 2 shows the results of microhardness measurements before and after aging of wires austenitized at different temperatures and cooled in air. Regarding those noted in Ref. [6], at temperature of 850 °C, the studied steel was partially austenitized and at the other ones a fully austenitic condition occurred.

In this figure, the value of x presents the distance from the center of cross section and r is the radius of drawn wire. The results show that after straining the wire, the hardness is increased from the center to surface of the wire cross section. This is due to the friction and redundant works through wire drawing increased from center to surface [7]. It should be noted that through hardness measurement from center to surface, the last point near the surface was selected at distance of $0.93r$ to remove the decarburized layer effect on the hardness value.

The results in Fig. 2 describe that with increasing the austenitizing temperature, the hardness is decreased. This is attributed to the austenite grain growth in higher temperature which leads to the coarser ferrite grain size and decrease of grain boundary area at room temperature causes to lower hardness [2]. The other important point found in this figure is the effect of strain aging on the microhardness distribution at the cross section. As can be seen, the strain aging leads to higher hardness of aged wires in comparison with that of the strained wires. Due to the concentration of solute carbon and nitrogen atoms, the dislocations are locked [1]. The concentration depends on the austenitizing temperature and cooling rate [2]. Since the strain is different at each point of the cross section, the effect of aging is different at each point. In the figure, it is observed that after aging, the hardness is decreased from center to surface of the wire cross section. This is in contrast to the hardness distribution of wire before aging. The hardness distribution after aging shows that the effect of aging phenomenon is decreased from center to surface of wire. This is attributed to the higher dislocation density at the surface which is generated due to the higher strain. In the region with the higher dislocation density, although some of the dislocations locked by solute elements, the remained ones are free dislocations and finally after dislocation locking due to aging there are more free dislocations in comparison with the regions having lower dislocation density. The more free dislocations make the flow of material easier and thus lead to lower hardness [1]. Consequently, after aging in the region with the lower dislocation density, there are more locked dislocations and the flow is hard.

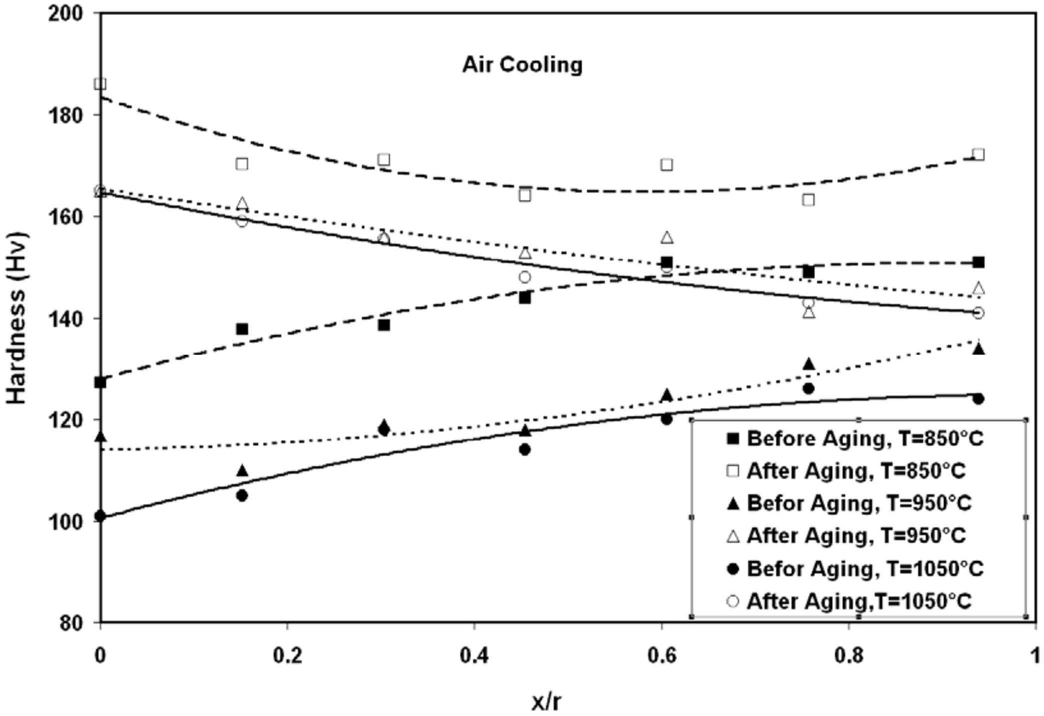

Fig. 2. The hardness distribution at the cross section of wires cooled in air and austenitized at different temperatures before and after aging.

Figure 3 presents the hardness distribution before and after aging of wires cooled by fan, air and in furnace from 1050 °C. As can be observed, before and after aging, the hardness of specimen cooled faster is higher. This is due to the finer ferrite grains formed from austenite phase.

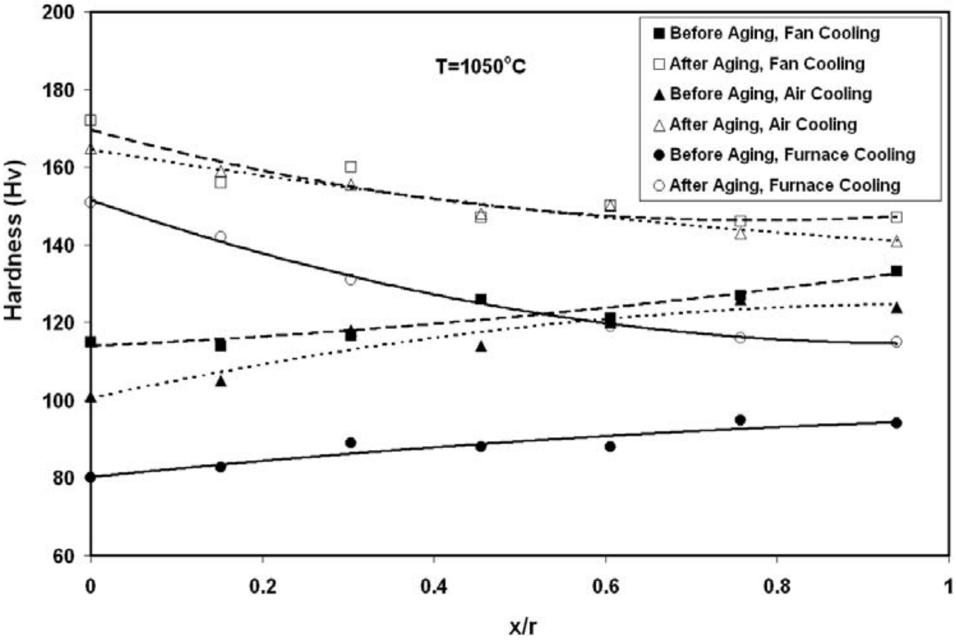

Fig. 3. The hardness distribution at the cross section of wires austenitized at 1050 °C and cooled at different rates before and after aging.

In this study, an aging index, ΔH , is defined as the difference between the hardness of each point at the cross section of wire before and after aging. In other words, the increase in hardness of each point due to aging is called aging index. The higher aging index of a specimen shows the higher aging sensitivity [1]. Figure 4 shows the index variation at the cross section of wires austenitized at different temperatures and cooled in furnace. The index is decreased from center to surface of wire. As described, after aging, the free dislocations are higher at the surface of wire, and thus the effect of aging on increasing of hardness is weaker. From this figure it is concluded that with increasing the austenitizing temperature, the aging index is increased. With increasing the temperature, the ferrite grain size formed from the austenite phase during cooling is increased. Thus, it may be expected that due to decreasing of grain boundaries area, which are the diffusion path [2], the dislocation locking due to solute diffusion should be decreased through aging and the index should be decreased. In order to describe the results shown in Fig. 4, it should be considered that with increasing the temperature, the solute atoms due to increasing of solubility is increased. Therefore, more dislocations are locked and the index is increased [1]. Moreover, after austenitizing at higher temperatures, the grain size of ferrite is coarser and thus the dislocation density after wire drawing is lower due to less grain boundaries leading to less pile up. Consequently, because of lower dislocation density, after aging and dislocation locking, the less free dislocations are available which leads to the increase of the aging index.

In Fig. 5, the index variations at the cross section of wires austenitized at 950 °C and the ones cooled with the different rates are presented. As can be seen, with increasing the cooling rate, the index is decreased. With increasing the cooling rate, the ferrite grains formed from austenite is decreased and solute atoms have less time to be formed as precipitations [8,9] and thus, more solute atoms are available. Therefore, it may be expected that due to more diffusion paths, i.e. grain boundaries, and solute atoms, the index should be increased. However it should be considered that due to the finer grains, more dislocations is generated through straining in wire drawing and thus after dislocations, locking in aging more free dislocations are available which leads to the decrease of the aging index.

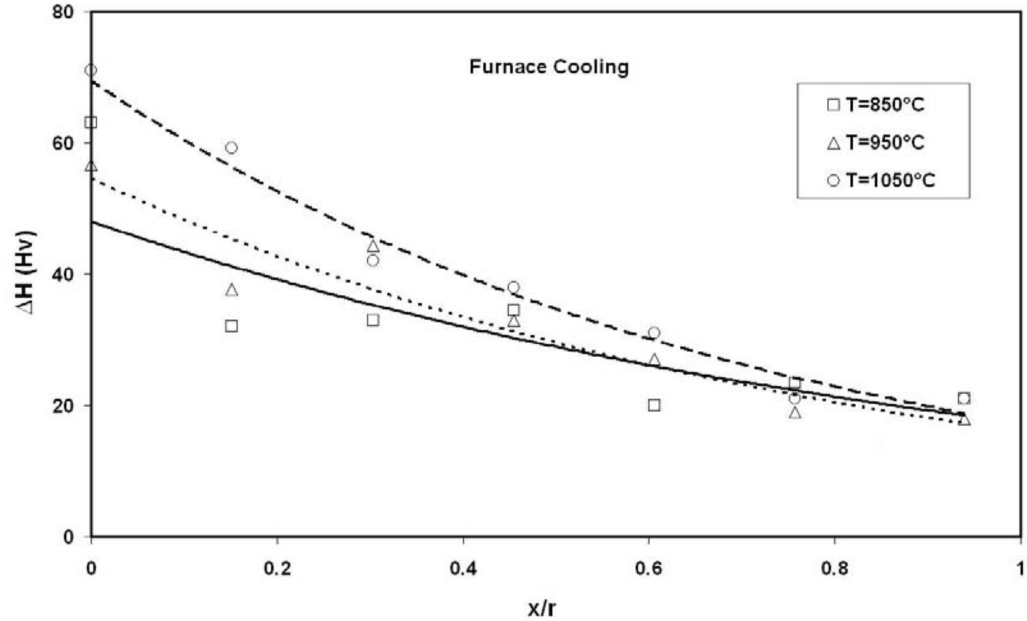

Fig. 4. The aging index distribution at the cross section of wires cooled in furnace and austenitized at different temperatures.

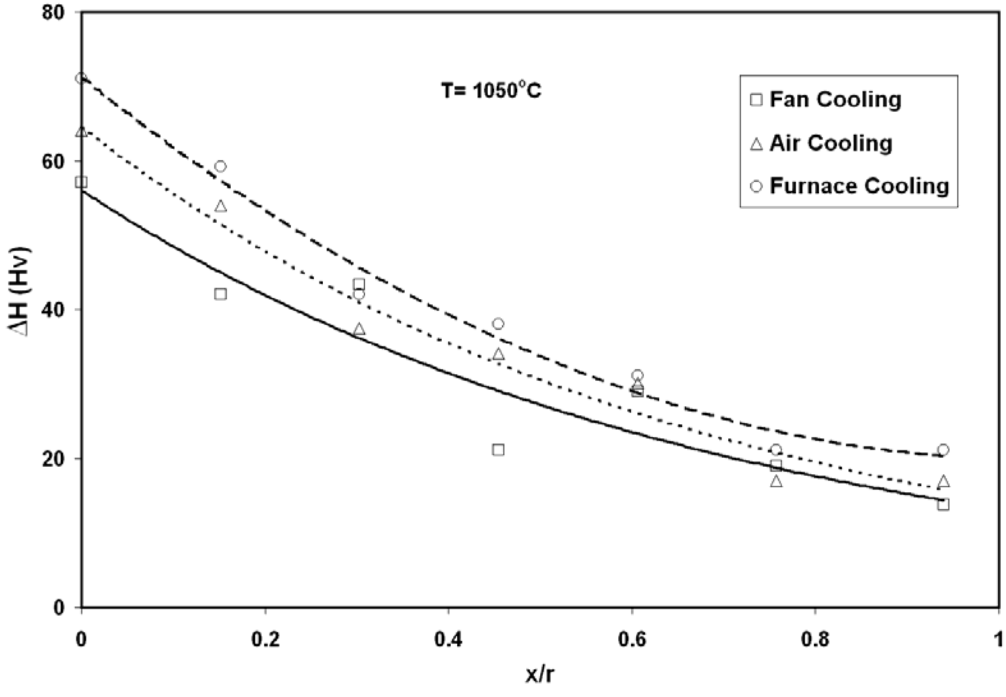

Fig. 5. The aging index distribution at the cross section of wires austenitized at 1050 °C and cooled at different rates.

In Fig. 6, the average of hardness values measured at the cross section of wires austenitized at different temperatures and cooled by fan are shown. The coarser ferrite grain sizes formed due to higher austenitizing temperature leads to lower hardness [2]. Also, the aging phenomenon leads to higher hardness. Figure 7 shows the effect of cooling media on the average hardness of wires before and after aging for a specific austenitizing temperature. As can be seen, with increasing the cooling rate, the average hardness is increased which is the result of the formation of finer ferrite grain size. The aging leads to increase of hardness. In Figs. 8 and 9, the effects of austenitizing temperature and cooling rate on the average of aging index are presented. The reasons for variations are the same as those mentioned for Figs. 4 and 5.

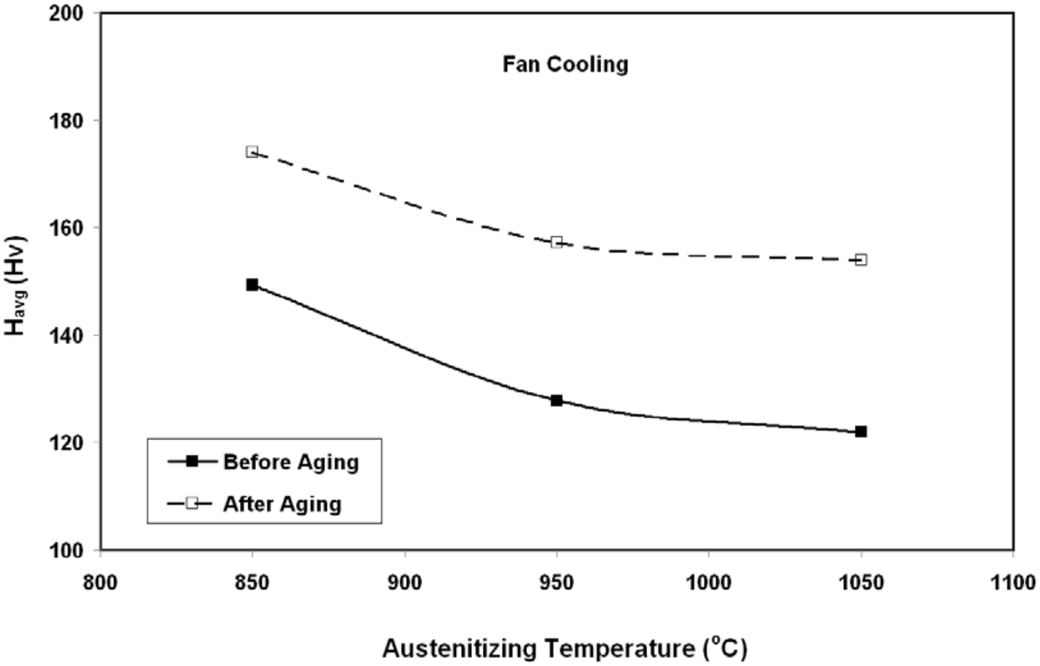

Fig. 6. The effect of austenitizing temperature on average hardness of wires cooled by fan before and after aging.

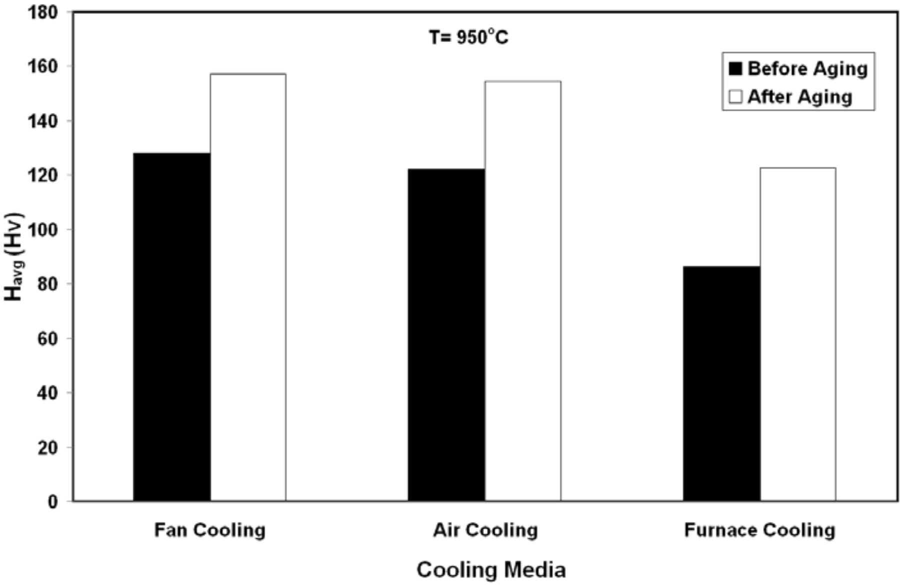

Fig. 7. The effect of cooling rate on average hardness of wires austenitized at 950 °C before and after aging.

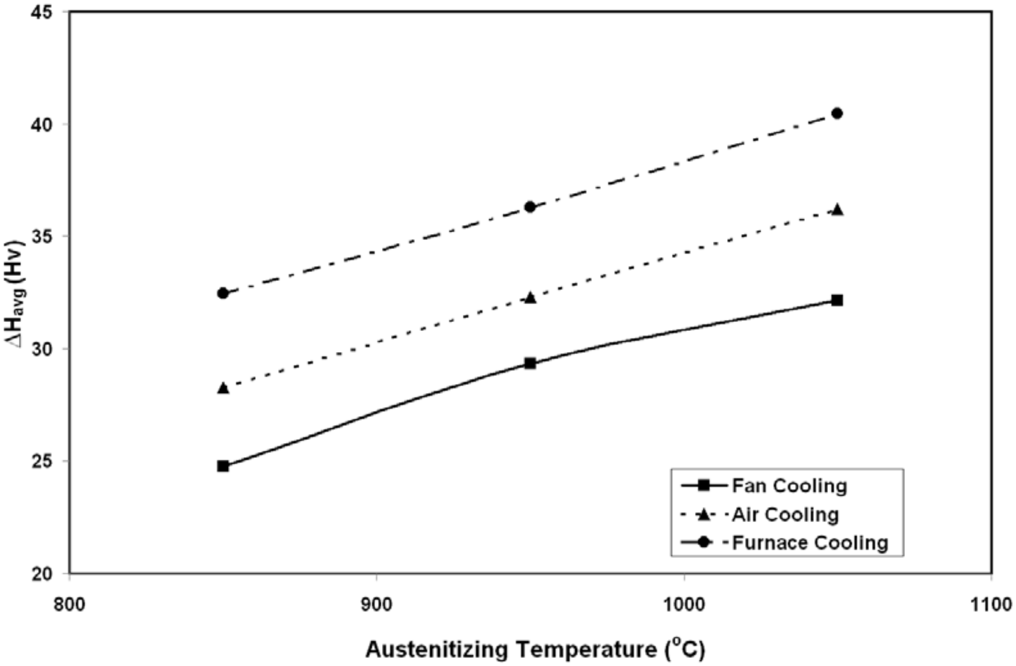

Fig. 8. The effect of austenitizing temperature on average of wires aging index cooled at different rates.

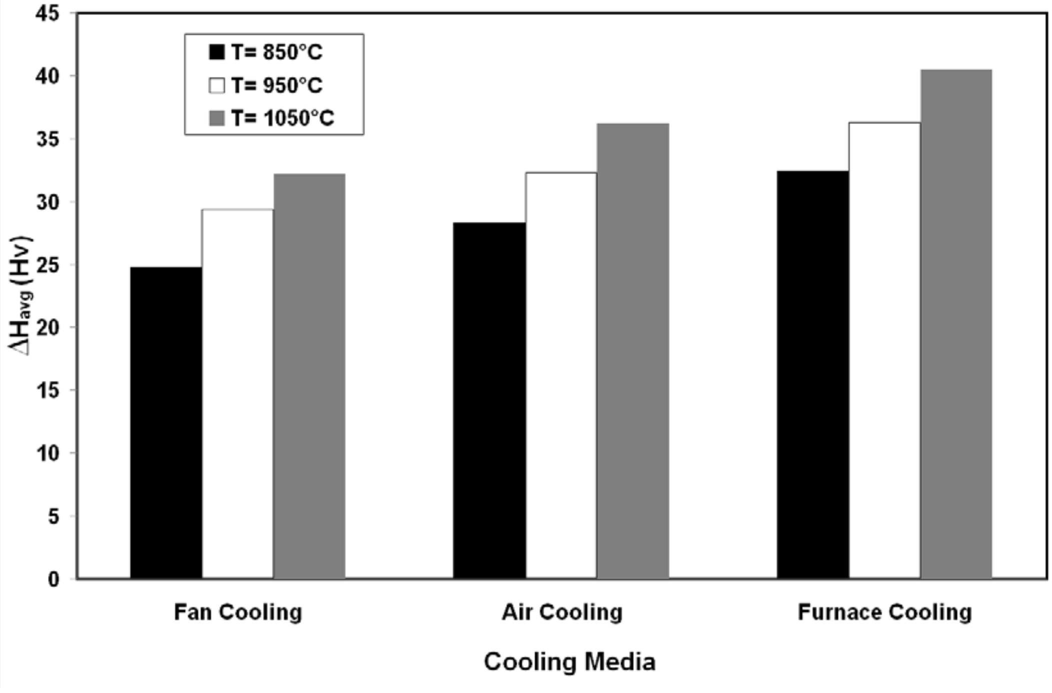

Fig. 9. The effect of cooling rate on average of wires aging index austenitized at different temperatures.

4. Conclusion

From the results presented in this research, the following conclusions can be mentioned:

1) After wire drawing and before aging of the wires, the hardness is increased from center to surface of their cross section.
2) After aging, the hardness is decreased from center to surface of wires cross sections.

3) The aging index is decreased from center to surface of wires cross sections.
4) With increasing the austenitizing temperature, the aging index is increased. However, the hardness value is decreased.
5) With increasing the cooling rate, the aging index is decreased. However, the hardness value is increased.

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