Influence of Aging Temperature on Mechanical Properties and Sound Velocity in Maraging Steel M350

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Abstract
In the present work, the influence of aging temperature on mechanical properties and sound velocity of Maraging steel M350 was investigated. For this purpose, first, samples were solution annealed at 825◦C for 2 hours and then age hardened at 510◦C-600◦C for 3 hours. Hardness, tensile and impact tests were used for determining mechanical properties and longitudinal ultrasonic velocity was used for determining sound velocity of the samples. The obtained results indicated that hardness, strength and sound velocity of the samples decreases with increase of ageing temperature, whereas, toughness of the samples increases directly with ageing temperature. These results were attributed to the dissolution of Ni_3(Mo,Ti) and Fe_2Mo precipitates and also to the formation of reverted austenite which are promoted by the increase of ageing temperature. Optical microscopy of the samples revealed that, in this case, the morphology of reverted austenite is mainly of grain boundary and interlath type. Further, a linear correlation between the mechanical properties and sound velocity of the samples was found that can be used in industrial applications.

Keywords: Maraging steel, Ageing, Reverted austenite, Sound velocity.

1. Introduction
Traditionally, destructive tests such as tensile testing or metallographic inspection are used to control the quality of the steel products and to prove that the properties are the same as the design stage. Sample preparation of these techniques is done through cutting a representative sample from the material and performing tests on this sample. Despite the necessity of having precise knowledge about the actual material properties used in the structure, destruction of the material is impossible in most cases due to safety requirements. Also, high testing costs should be added to drawbacks of destructive tests. Therefore, determining the properties of materials with nondestructive techniques has attracted the researchers' attention in recent years.
Maraging steels with unique combination of properties such as ultrahigh strength, high toughness, good formability and weldability have received attention of many strategic industries [1)]. These steels receive their strength and toughness from martensitic transformation followed by age hardening. Since the martensitic transformation only involves an austenitic to martensitic transformation of Fe-Ni, and does not involve carbon to any considerable extent, the martensite which is formed is relatively ductile [2)]. The level of strength attained during age hardening depends on the time and temperature of ageing process. Results of earlier studies show that the peak hardness and strength of these alloys is achieved by the formation of metastable Ni_3Mo, Ni_3Ti and Fe_2Mo precipitates [3-7)]. Prolonged ageing or overageing at higher temperatures results in the formation of reverted austenite [8)].
Few investigations have been performed to determine the properties of maraging steels using nondestructive techniques [12,13)]. The main purpose of this work is to find out the influence of aging temperature on mechanical properties and sound velocity of Maraging steel M350.

2. Experimental procedure
In this work, raw material of M350 steel was provided in the form of extruded bar with a diameter of about 60 mm. Composition of the alloy is given in Table 1.
Raw material was initially solution annealed at 825 °C for 2 hr in a vacuum furnace. Then, samples for tension and impact tests were prepared from the annealed material according to the ASTM E23 and ASTM E8 standards, respectively. After that, ageing treatment was carried out on samples at temperature range of 510 to 600 °C for 3 hr in the same vacuum furnace.
Three tensile samples were tested for each ageing condition at a strain rate of about 0.01 s^{-1}. On each sample, 5 hardness values were taken and the average value was reported. An optical microscope (OM)

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Table 1. Chemical composition of M350 steel used in this work.

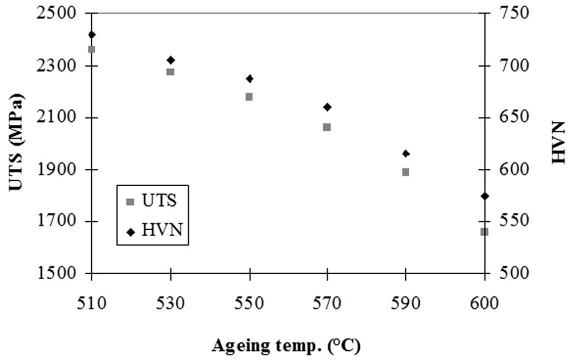
Element	Ni	Co	Mo	Ti	Al	Mn	Si	C	Fe
%Wt	17.88	12.03	3.93	1.54	0.17	0.03	0.05	0.004	.Bal

was used to study the microstructure of samples. Specimens for OM study were first mechanically polished and then etched using an aqueous solution consisting of 30 ml H_2O, 5 gr $CuCl_2$, 40 ml HCl and 25 ml ethanol. Pulse-echo technique was used to measure the ultrasonic velocity within the samples. Longitudinal ultrasonic wave was produced using a 20 MHz TR normal probe.

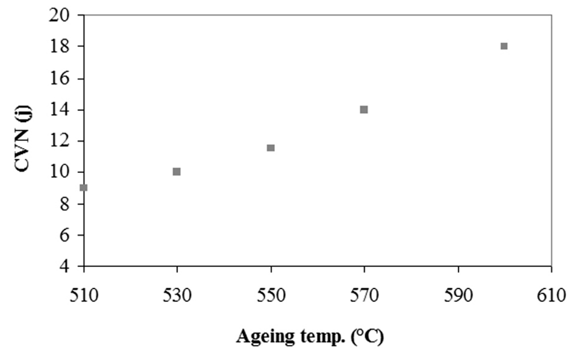
3. Results and discussion

Fig. 1 shows the variation of mechanical properties with ageing temperature. As shown in Figs. 1a and 1b, the maximum hardness and strength of the alloy (2361 MPa and 730 HV, respectively) and also the minimum toughness (9j) is achieved after 3 hr of ageing at 510°C. Also, results of TEM studies [6,13] show that ageing of this alloy at 510°C leads to the formation of Ni_3(Ti,Mo) and Fe_2Mo precipitates. These precipitates have an ellipsoidal morphology and increase strength of the alloy. Increase in temperature results in the dissolution of these strengthening precipitates in the matrix which locally enhances the concentration of Ni element, producing preferential sites for nucleation of austenite phase. In Fig. 1,it can be seen that hardness and strength values decrease with an increase in ageing temperature, whereas, toughness values decrease.Viswanthan et al[14]. suggested that this trend be attributed to enhanced formation of retained austenite with an increase in ageing temperature. Depending on the temperature, time and rate of heating different morphologies of austenite (such as grain boundary, interlath and Widmanstätten) may be produced in the martensitic matrix [14-16]. In the present work, microstructural study of the samples showed mainly grain boundary and interlath morphologies of austenite. Fig. 2 shows typically microstructure of a sample aged at 600°C. Small and large arrows represent grain boundary and interlath morphologies of austenite, respectively.

Fig. 3 shows the variation of sound velocity with ageing temperature. It is observed that increase in temperature brings about constant decrease in sound velocity. Rajkumar et al. and Yeheskel[11,12] investigated the effect of age hardening on sound velocity in maraging steel 250. They found that with the onset of retained austenite formation, the longitudinal sound velocity decreases severely. They attributed this behavior to the increase in Ni concentration in the matrix that reduces elastic modulus. Regarding the relationship between elastic modulus (C), sound velocity (v) and density (ρ) of metals ($C= \rho v^2$), elastic modulus has a considerable effect on sound velocity.



(a)



(b)

Fig. 1.Variation of (a) hardness and strength values,and (b) toughness values of the samples with ageing temperature.

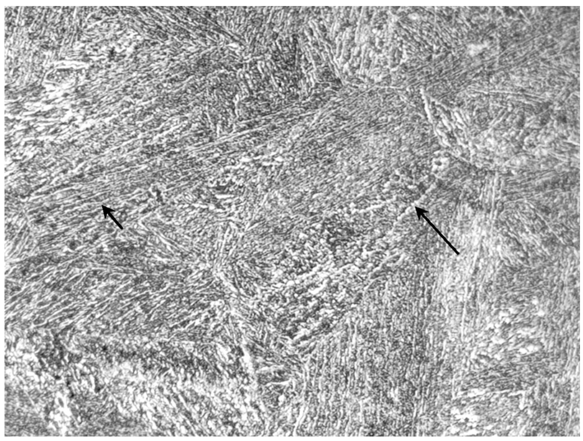


Fig. 2.Optical microstructure of the sample aged at 600°C.

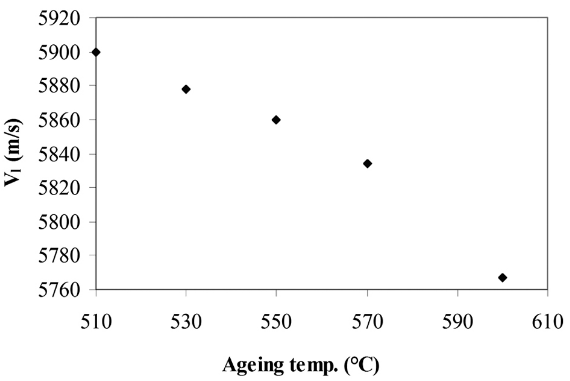


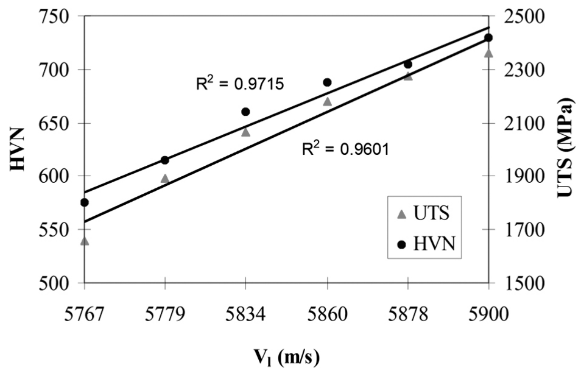
Fig. 3.Variation of the sound velocity with ageing temperature.

One of the important findings of this research is the linear relationship between mechanical characteristics and sound velocity of maraging steel 350. Fig. 4a shows the linear relationship between sound velocity, hardness and strength with a positive slope. Fig. 4b shows the linear relationship between the sound velocity and toughness of the alloy which conversely has a negative slope. This difference in the relationships is related to the properties of austenite phase. This phase has an FCC crystal structure, high ductility and low hardness.

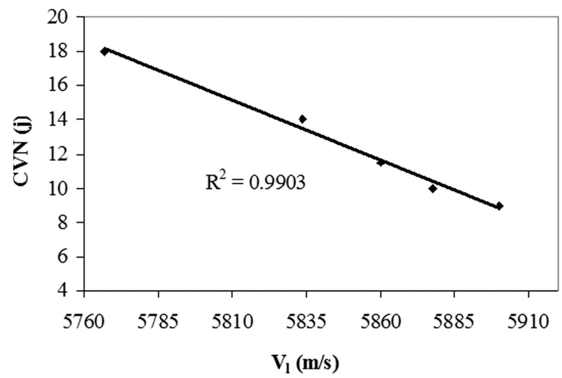
On the other hand, formation of retained austenite enhances the Ni concentration in the matrix, decreasing elastic modulus and sound velocity of the alloy. These linear relationships can be used for determining the characteristics of heat treated parts or even controlling of heat treatment processes nondestructively, and therefore are important from an industrial viewpoint.

4. Conclusion

In this research the influence of ageing temperature on mechanical characteristics, ultrasonic velocity and also their relationships were investigated in maraging steel M350. It was found that with increase in ageing temperature strength, hardness and sound velocity of the samples decrease, however, toughness of the samples increases. These trends were related to the enhanced formation of retained austenite with increases in ageing temperature. This phase has an FCC crystal structure, high ductility and low hardness. On the other hand, formation of retained austenite enhances the Ni concentration in the matrix, decreasing elastic modulus and sound velocity of the alloy. Further, a linear relationship between mechanical properties and sound velocity of the samples was found, which is important from an industrial viewpoint.



(a)



(b)

Fig. 4.Relationship between sound velocity and (a) hardness and strength, and (b) toughness of the alloy.

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