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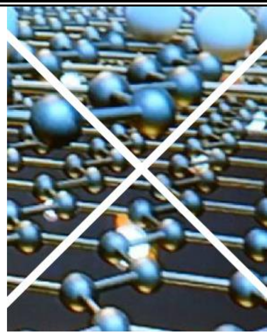

INVESTIGATING THE RESIDUAL STRESSES THAT FORMED AFTER THE HARDENING HEAT TREATMENT OF AISI/SAE 4140 STEEL BY ULTRASONIC TESTING METHOD

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Abstract

Residual stresses may form after various machining and heat treating applications, thermo-mechanical methods, unsuitable usage of machining tools and cutting parameters. Residual stresses may also increase up to very high levels in consequence of hardening and surface treatment of metallic materials. Residual stresses can form after the production of structural and mechanical components and deteriorate the fatique and service life, dimension stability, technical security requirements. Hence, the residual stress level of such parts should be decreased to reasonable values to increase the service life and reduce the costs.
In this work; the effects of tempering temperature on residual stresses of AISI/SAE 4140 steel alloy that widely used in mechanical part industries after hardening heat treatment is investigated. 15 samples in dimensions of 40x40x120 mm are heat treated by normalization to ensure uniform beginning microstructures. Then, hardening heat treatment is applied with 6 different tempering temperatures besides 2 untempered samples. After hardness surveys, all samples are tested with ultrasonic flow detector. Longitudinal and surface waves are used in ultrasonic examinations. Whether the residual stress in test materials increase the sound velocity of the ultrasonic wave decreases. The relationship between travel speeds of ultrasonic waves and residual stresses are estimated by mathematical equations.

Keywords: Residual stresses, Ultrasonic testing, Heat treating of steels.

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1. Introduction

Residual stresses are formed after the production of various mechanical parts and they significantly affect the properties of materials mainly as fatigue strength, service life, dimensional stability and safety. Residual stresses can occur as a result of various machining and manufacturing methods. These applications include; turning, milling, cutting, grinding, casting, forging, welding, rolling, extrusion, electro-erosion, laser manufacturing, chemical and thermo-chemical processes. Residual stresses are examined in two groups as macro and micro residual stresses. Macro residual stresses are present in only a part of the material, while micro residual stresses are mostly located in the whole cross section of the material. These stresses are in the tension or compression states. When the work pieces are allowed to cool down after some thermo-mechanical processes such as heat treatment or forging, rolling, the outermost of the part will lose heat faster than the core part, depending on the cooling rate, this temperature difference between the core and the surface will create a large amount of residual stresses in the part. While the surface of the part wants to shorten the size due to heat loss, the core part desires to shorten less due to slower cooling. In other words, the core region will apply compressive stress to the surface while the surface region will apply tensile stress to the core. This stress difference will create a large amount of residual stress throughout the part.

Stress relief annealing is performed to reduce the internal stresses present on the parts to a level that will not cause problems. Internal stresses can occur from many different reasons, such as rapid cooling (cooling stresses) due to the temperature difference between the wall and core, hardening with increasing volume in martensite transformation (transformation stresses), plastic shaping such as straightening and bending, machining, welding. Internal stresses make it very difficult to machine metals. In addition, they cause deformation of steel during processing or heat treatment after plastic deformation. Therefore, these stresses should be relieved as much as possible [1, 2].

In stress relief annealing, internal stresses are reduced by creep events. There is no microstructure change in this annealing type. In stress relief annealing, the temperature should be selected above the highest usage temperature but below the temperature at which property changes are encountered. As a result, the part is stress relieved or tempered immediately after the curing process and an adequate amount of the trapped atoms are allowed to return to their former relaxed positions. The temperature at which the stress relief annealing is applied varies according to the composition of the steels. It is approximately in the range of 550-650 ºC for plain carbon and low alloy steels and 600-750 ºC for hot work tool and high speed steels. The most practical way to avoid the formation of thermal stresses during cooling is to cool the parts slowly in the furnace and then remove them from the furnace and cool them slowly in calm air. In stress relieving operations of very large tools or machine parts that are desired to be free from residual stresses, the cooling rate should initially be very slow. Stress relief annealing is performed at a temperature 25 ºC below the normal tempering temperature of hardened and tempered steels [1-4].

Rosen Stein proposed a method for determining the effectiveness of stress relief. When the hardened and tempered steel is subjected to the stress relief treatment, it is possible to optimize the time and temperature for the stress relief annealing to be applied, without compromising the hardness [3].

The methods used for the detection of residual stresses are evaluated in two groups as destructive and non-destructive. Among the destructive tests; X-Ray test, Hole-drilling methods are widely used. X-Ray method gives optimum results at maximum depths of 10 µm. In addition, the initial setup cost of the equipment is high and the test system is expensive. The method is considered destructive in terms of sample preparation. The hole-drilling method provides the opportunity to scan the entire section of the material to be examined in a short time [5].

Barkhausen Noise Method and Ultrasonic Inspection Method stand out among the non-destructive methods. Detection of residual stresses by ultrasonic examination come front in terms of economy, practicality and not destroying the part to be examined. In addition, parts can be examined partially or throughout the cross section. CETIM (Center Technique Des Industries Mecaniques) inspection center established in Senlis-France, determines residual stresses by ultrasonic examination method. Residual stresses in materials can be detected with the ultrasonic test device developed in CETIM Laboratories and used widely in many developed industrial countries under license. The difference of the system from conventional ultrasonic inspection devices is that it is computer-aided. In addition, Integrity Testing Laboratory, based in Toronto, Canada with the UCC (Ultrasonic Computerized Complex) device, which was developed with the cooperation of the National Academy of Sciences in Ukraine, residual stresses in materials can be detected by computerized devices [6].

Detection of residual stresses by ultrasonic inspection method basically consists of passing the ultrasonic wave through tensioned and non-tensioned materials and consequently examining the change in the speed of sound of the wave. In order to perform this examination in a healthy way, it is necessary to perform the calibration precisely before measurement. Also, a meticulous inspection should be made to minimize the reading errors on the oscilloscope screen. In ultrasonic examination method, the grain size of the part to be examined should also be taken into consideration. The larger the grain sizes of the part, the probability of the greater sound waves to scatter and therefore the attenuation of sound waves may occur. [7]

There are some studies on the determination of residual stresses in materials by using sound techniques. Bray and Junghans; put forward their studies to determine residual stresses after heat treatment of steel plates with the help of Longitudinal Surface Waves [8]. Duquennoy et al. stated in their work that the stresses in materials can be measured with Rayleigh waves [9]. Oettel; using the 'Hole Drilling' technique, the uncertainties in the detection of residual stresses have been studied [5]. Valaszek et al. proposed in their study that residual stresses are directly related to the material microstructure in calculation with ultrasonic examination method [10].

In this study; SAE/AISI 4140 steel alloy has been subjected to hardening heat treatment after normalization heat treatment in order to create residual stresses at different levels and the effect of different tempering temperatures on residual stress levels has been determined by conventional ultrasonic inspection method. The present study clarifies the determination of the amounts of residual stresses in variously heat treated SAE 4140 steel alloy by using ultrasonic testing method and empirical residual stress equations.

2. Materials and Methods

2.1. Experimental Material

The material used in the experimental study was 42 CrMo4 (SAE 4140, 1.7225) selected from the heat treatable steel group. The chemical composition of alloy is given in Table 1. Optical Emission Spectral analysis results in Table 1 confirm the material standard specification [11].

Table 1. Optical Emission Spectral analysis of 4140 alloy

Element	C	Si	Mn	Cr	P	S	Mo	Fe
(Weight %)	0.41	0.25	0.82	0.94	0.020	0.028	0.23	remaining

Test samples were cut by 40x40x120 mm in dimensions. All surfaces were machined and grinded.

2.2. Heat Treating of Samples

All of the test samples were first subjected to normalization heat treatment before hardening operation to reduce the micro-structural differences as much as possible. With normalization, it is aimed to refine the grain size and to provide a homogeneous beginning microstructure. In addition, since the normalization process is cooling of the material in calm air following the austenitization temperature, the residual stresses are aimed to be equal in all samples as much as possible.

Normalization heat treatment

15 Samples prepared from 4140 alloy with a size of 40x40x120 mm were preheated at 400 C° for 1 hour and then the temperature is increased up to 870 C ° austenitizing temperatures for 2 hours and then cooled in calm air directly to room temperature. The average hardness test results taken from the samples after normalization were found 320 HV-Hardness Vickers scale (1030 Mega-Pascals). All samples are normalized. Normalization heat treatment is schematically given in Figure 1.

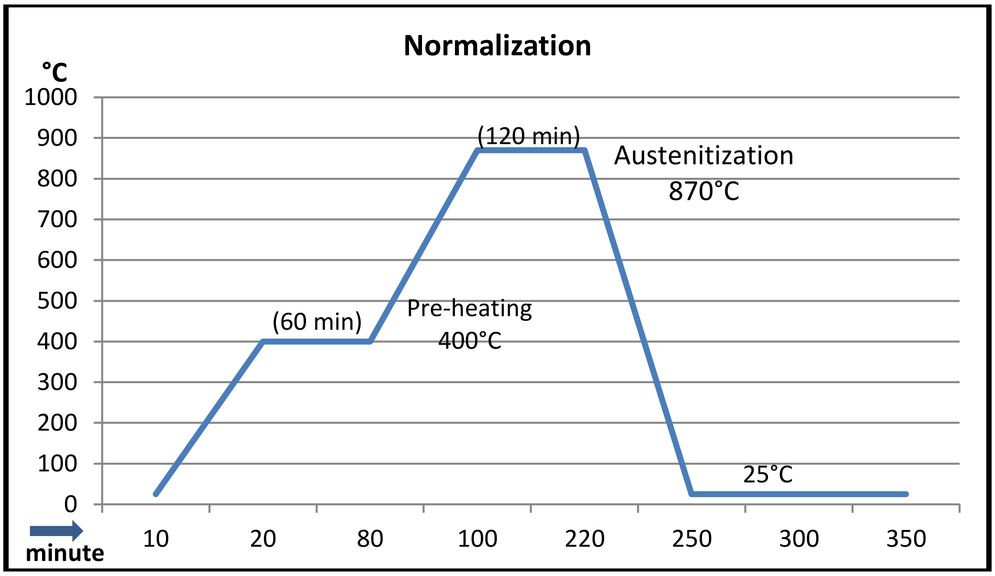


Figure 1. Normalization heat treatment

Hardening heat treatment

After normalization, the hardening heat treatment is applied. The hardening heat treatment includes preheating, austenitizing, cooling in oil bath and tempering processes respectively. Sample 1 is just normalized. 14 samples except Sample 1 were subjected to hardening heat treatment after normalization. In hardening treatment; 14 parts were preheated at 400° C for 1 hours of time and from behind austenitized at 850° C by 2 hours. Then, quenching process was applied in a homogeneous dynamic oil bath at 60°C. 12 samples were tempered at 6 different temperatures (100, 200, 300, 400, 500, 600 °C) to obtain different strength values and consequently to create different amounts of residual stresses. Two of the samples were not tempered after hardening for obtaining the highest residual stress values among the other all hardened samples. Hardening heat treatment operation is schematically given in Figure 2.

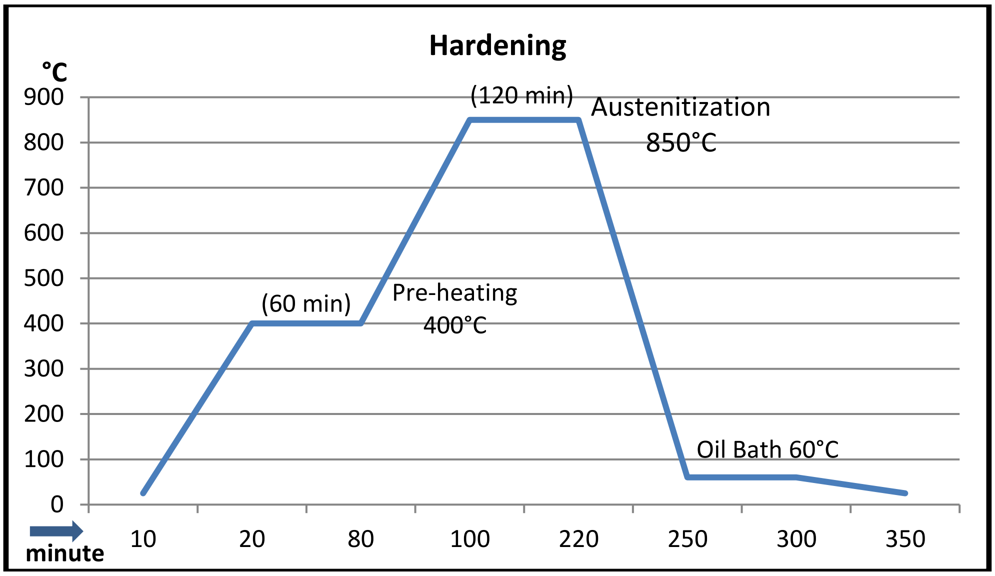


Figure 2. Hardening heat treatment

2.3. Micro-structural Investigations

Only normalized (Sample 1) and one of the hardened-tempered samples (Sample15) microstructures were investigated by a metallurgical microscope for comparison of structures as examples. These two samples are grinded by emery paper having the mesh numbers of 240 up to 800 and polished with 3µm diamond paste and finally etched by 3% nitric acid solution.

2.4. Ultrasonic Inspection after Heat Treatments

Krautkramer brand USL32 model ultrasonic examination device is used in experimental studies as given in Figure 3. The device has an oscilloscope screen and works with a reading sensitivity of ±2%. Calibration was performed with K1 standard calibration block according to EN ISO 2400 standard before measurements [12].

15 samples were subjected to ultrasonic examination method by creating both surface waves and longitudinal waves separately to obtain the data required to measure the residual stresses whether they contain. Longitudinal waves, appear as a technique that is measured with normal (linear sound wave generating) probes [7-9, 13]. Surface waves (LCR- Longitudinal Waves Reflected at a Critical Angle) can penetrate the surface parts of the material and only to a depth of wavelength. LCR waves are formed as a result of the positioning of the probes that travel just below and parallel to the surface of the inspected material at a critical angle. LCR waves are much more susceptible to stress than other types of waves, despite their propagation through the surface, without being affected by the hardness and other physical properties of the material [8].

Longitudinal and surface waves (L_{CR}) are used in ultrasonic testing method. 2MHz normal probe with a diameter of 24mm is selected. Surface waves are produced with a critical angle in a water bath for reducing velocity loss problems.

The ultrasonic test apparatus and the device for surface waves are given in Figure 3.

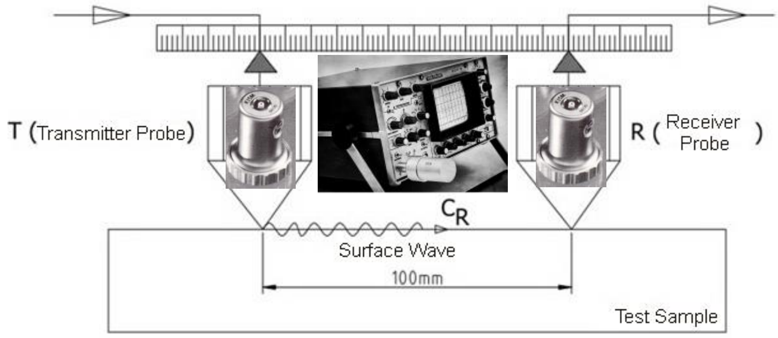


Figure3. Schematic apparatus of ultrasonic testing instrument in a water bath

The calibration distances on the 50 and 100 mm surface of the K1 calibration block are taken as reference. The 50 mm surface of the K1 block is calibrated to 2.5 scales on the oscilloscope screen, and the 100 mm surface to 5.0 scales. Thus, the size of the test samples of 100 mm, which is the control distance for surface waves, corresponds to 5 as a scale on the oscilloscope screen. According to this reference value, the different stresses created on the samples will appear on the oscilloscope screen in a different position than the 5 scale value depending on the change in the sound velocity of the surface wave.

Based on these values on the oscilloscope screen obtained as a result of the ultrasonic examination of all samples with surface waves, the sound velocities are calculated using the following Equation 1, according to the K1 block as reference [7, 14].

$$CR2 = [CR1 \times d]/[k \times T] \quad (1)$$

In Equation 1; CR (1) is the surface wave sound velocity of the known (reference) material, CR (2) is the surface wave sound velocity of the unknown (estimated) material, the k value is the scale factor of the ultrasonic instrument calibration screen, and T is the scale value read on the oscilloscope screen of the ultrasonic device. The sound round trip time (t) is calculated with the Equation 2 given below [7, 14].

$$t = x/c \quad (2)$$

In Equation 2, 'x' refers to the distance of the sound wave travels, and 'c' refers to the speed of the sound within the material.

3. Results and Discussion

3.1. Strength values of samples after heat treatments

Mechanical strength values of 14 samples are estimated by Vickers hardness test HV10. The strength values are given in Table 2.

These strength values in Table 2 are obtained by converting them from Vickers hardness test values into the MPa (or N/mm^2) unit [15].

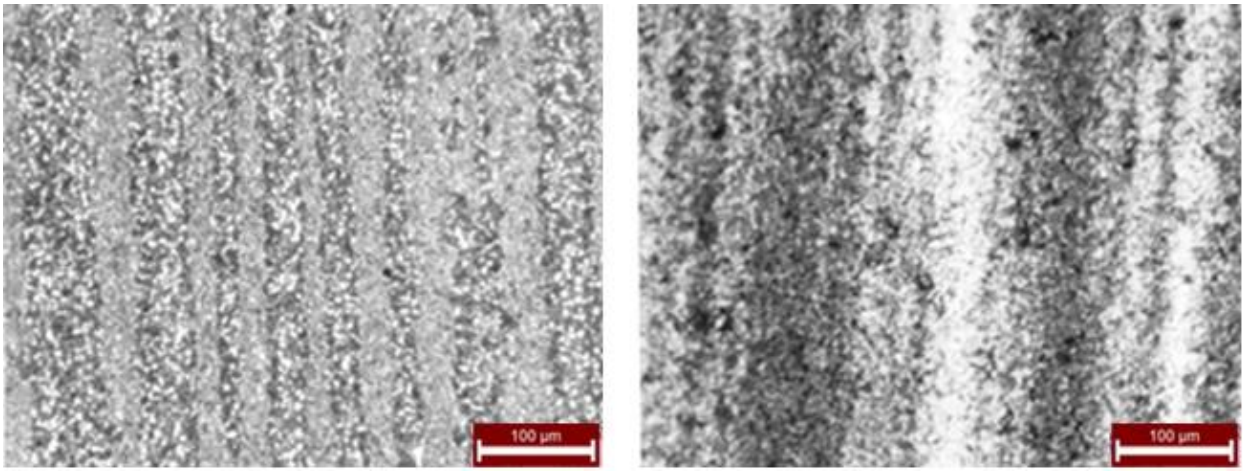
Table 2. The strength values of samples after heat treatments

Sample No.	13	12	10	11	8	9	6
Tempering Tem. (ºC)	600	600	500	500	400	400	300
Strength Values (MPa)	1255-1420	1385-1480	1520-1520	1550-1555	1420-1455	1700-1845	1775-1880

Sample No.	7	4	5	2	3	14	15
Tempering Tem. (ºC)	300	200	200	100	100	Untem.	Untem.
Strength Values (MPa)	1840-1850	1775-1850	1880-1920	1880-1930	1995-1995	2040-2040	2040-2040

3.2. Microstructures of samples

Microstructures of Sample 1 (only normalized sample) and Sample 15 (normalized and hardened) are given in Figure 4 as examples.



(a) (b)

Figure 4. Microstructures of (a) Sample 1 and (b) Sample 15

Sample 1 exhibits a homogenous and fine grained ferritic-pearlitic microstructure while Sample 15 has relatively less homogenous but dominantly bainitic and martensitic microstructure. Darker regions are pearlitic and lighter grey are ferritic structure in Figure 4-(a). A uniform wrought oriented microstructure is observed in normalized state of samples.

Darkest phases are martensite, dark regions are bainite and light grey regions are pearlite and lighter phases are ferritic microstructure in Figure 4-(b) in hardened and tempered condition. A uniform wrought but a few less amount of oriented microstructure is determined in hardened and tempered state of samples. Both of the samples have showed wrought micro-structure as visible in Figure 4. As the tempering temperature after hardening operation increases, the amount of martensite and bainite phases decreases. Normalization and hardening heat treatments did not significantly affect the wrought beginning microstructure.

3.3. Ultrasonic Testing of Samples

Oscilloscope scale values estimated from ultrasonic testing device

Sample 1 as an example, which has only been subjected to normalization process, is placed in Equation 1 according to the 5.004 scale value obtained from the oscilloscope screen as a result of the examination with surface waves.

$$CR2 = [CR1 \times d]/[k \times T]$$

$$\text{CR2} = [3013.6 m/sec \times 100 mm]/[20 \times 5.004] \Rightarrow \text{CR}_2 = 3011.2 \text{ m/sec.}$$

Time for travel of sound was estimated for Sample 1 by using the Equation 2,

$$t = x/c$$

$$t = (100 mm/1000)/3011.2 m/sec$$

t = 0.000033209 sec $\Rightarrow$ t =33.21 µsec

The values for all samples were calculated in this way. Ultrasonic velocities of surface waves are listed in Table 3.

Table 3. Ultrasonic velocity of surface waves

Sample Screen Scale No.	Scale No. on Oscilloscope Screen	Sound travelling time (µsec)	Velocity of Surface wave (m/sec)
TK_1	5.000	33.18	3013.6
T_1	5.004	33.21	3011.2
T_{12}	5.054	33.54	2981.4
T_{13}	5.050	33.51	2983.8
T_{10}	5.060	33.58	2977.9
T_{11}	5.065	33.61	2974.9
T_8	5.075	33.68	2969.1
T_9	5.080	33.71	2966.1
T_6	5.085	33.74	2963.2
T_7	5.083	33.73	2964.4
T_4	5.090	33.78	2960.3
T_5	5.090	33.78	2960.3
T_2	5.090	33.78	2960.3
T_3	5.095	33.81	2957.4
T_{14}	5.150	34.18	2925.8
T_{15}	5.150	34.18	2925.8

TK_1: *calibration block*

Similarly as surface waves, all samples were tested by ultrasonic examination using longitudinal sound waves. In the calibration process made with the 25 mm part of the K1 block, the device is calibrated to 150 mm. Since the length of the part to be examined is 120 mm, the sound echo that appears on the oscilloscope screen as a result of the longitudinal wave test of the non-stressed (normalized sample no.1) on the oscilloscope screen after calibration will increase to 8,000. The result of all other samples by taking this value as a reference and the sound trip times and sound velocities calculated based on these results are given in Table 4. The longitudinal wave velocity for the K1 calibration block given in EN ISO 2400 is 5920 m/sec. Based on this reference value in longitudinal waves, according to the value read on the oscilloscope screen, this time by writing the longitudinal wave velocity instead of the surface wave velocity in the relation. The longitudinal sound wave velocities of all samples are calculated using the Equation 1. As an example, the sound velocity of the Sample 1 (normalized sample) in Table 4 was calculated as follows:

$$CR2 = [CR1 \times d]/[k \times T]$$

$$CR2 = [5920 m/sec \times 120]/[15 \times 8.02]$$

$$CR2 = 5905.23 \text{ m/sec}$$

Again; time for travel of longitudinal sound was estimated for Sample 1 by using the Equation 2,

$$t = x/c$$

$$t = (120mm/1000)/5905.23\ m/sec$$

t = 0.00002032 sec. ⇒ t = 20.32 µsec

The values for all other samples were calculated in this way. By using these values, Table 4 was obtained for longitudinal waves. By these ultrasonic testing values resulted with longitudinal waves, Equation 3 is used to evaluate the residual stresses occurred in samples [8].

$$\Delta\sigma = \left(\frac{E}{L \times t0}\right) \times (t - t0) \qquad (3)$$

Equation 3 gives the amounts of residual stresses evaluated by ultrasonic testing [8]. $\Delta\sigma$ refers to residual stress value, L is the acoustoelastic constant of inspected material, t value refers to the sound travel time of the ultrasonic wave in the stressed material, and the value t_o the sound travel time of the ultrasonic wave in the unstressed state of material in Equation 3.

Table 4. Results of ultrasonic test applied by longitudinal waves.

Sample Screen Scale No.	Scale No on Oscilloscope Screen	Velocity of Longitudinal wave (m/sec)	Sound travelling time (μsec)	Residual Stress Value (MPa)
TK_1	-	5920.00	-	-
T_1	8.02	5905.23	20.32	0
T_{12}	8.05	5883.23	20.40	357.9
T_{13}	8.06	5876.00	20.42	447.4
T_{10}	8.06	5876.00	20.42	447.4
T_{11}	8.07	5868.60	20.45	581.6
T_8	8.08	5861.40	20.47	671.1
T_9	8.08	5861.40	20.47	671.1
T_6	8.09	5854.14	20.50	805.3
T_7	8.10	5847.00	20.52	894.8
T_4	8.10	5847.00	20.52	894.8
T_5	8.10	5847.00	20.52	894.8
T_2	8.11	5840.00	20.55	1029.0
T_3	8.12	5832.51	20.57	1118.5
T_{14}	8.20	5775.61	20.78	2058.0
T_{15}	8.20	5775.61	20.78	2058.0

***TK_1:** calibration block*

If the residual stress estimation described above is applied to sample 15 as an example,
Elasticity modulus (E) of 4140 is taken approximately as 200GPa. [16], acoustoelastic constant 'L' for 4140 alloy is 2.2 by positive value because of the compression type of residual stresses and 2MHz normal ultrasonic probe [17], t and t_0 values are taken from Table 4.

$$\Delta\sigma = \left(\frac{E}{L \times t0}\right) \times (t - t0)$$

$$\Delta\sigma = \left(\frac{200GPa}{2.2 \times 20.32}\right) \times (20.78 - 20.32)$$

$$\Delta\sigma = 2058 \text{ MPa.}$$

Residual stress values of all samples are estimated by this way and listed in Table 4. Whether the residual stress values of the heat treated material increases the velocity of the ultrasonic wave decreases. As the tempering temperature increases the residual stresses in samples decreases.

Primarily, there are many studies related with ultrasonic inspection of resudial stresses of various material groups that formed in different reasons such as welding, heat treating, machining, forming etc. [18-30]. But this study especially focuses on the ultrasonic inspection of resudial stresses of SAE/AISI 4140 alloy with a equalized beginning homogenous normalized structure after the hardened and tempered conditions.

4. Conclusions

Residual stresses in metallic materials can be increased by various heat treating operations. Hardening heat treatment significantly affects the residual stress levels in steels. In this study as the tempering temperature in hardening operation increases, the amounts of hard phases like martensite and bainite decreases and also the hardness values and residual stress levels decreases.
Residual stresses that occur after heat treatments can be detected by ultrasonic examination method. The advantages of the

method include that it is practical, non-destructive and the parts can be examined partially or completely.

When ultrasonic waves are passed through a part having residual stress, there are significant changes in the behavior of the sound waves compared to the part without residual stress. The most important case is the difference in the speed of sound of the wave. The ultrasonic wave velocity in the part containing residual stress decreases as compared to the part without residual stress. In other words, as the residual stress in the part increases, the sound velocity of the ultrasonic wave decreases.

Longitudinal waves and surface waves were used in this ultrasonic inspection study. Since the *L* (acoustoelastic) coefficient of the experimental material for surface waves could not be found on literature, longitudinal waves were used on estimations of the residual stresses in this study. Besides, longitudinal and surface waves both exhibited by the same trend in this study as seen from the results.

Based on the data obtained with longitudinal and surface waves, each increase in residual stresses in test materials resulted in the decrease of sound wave velocity.

The estimation of strength value accuracy depends on the calibration of the ultrasonic device, the oscilloscope screen reading errors, the tested materials physical properties and constants, screen calibration of the device, uncertainties of the test conditions and standard deviation of the test results.

Tests were made with a conventional ultrasonic inspection device. In fact, there are special trade ultrasonic inspection devices that supported with detailed complex equipments and computerized units. Thus it is much more accurate to estimate the residual stresses in various materials by these instruments. But this study focused on the relationship between the ultrasonic wave velocities and the residual stresses of heat treated samples and also to determine their values by estimation practically.

It has been determined in this study that increasing tempering temperature in hardening operation decreased the residual stress levels with decreasing ratios of hard phases such as martensite and bainite and resulted in lower stress values on samples according to residual stress measurements by ultrasonic inspection method promoted with empirical equations.

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