# INVESTIGATING THE MICROSTRUCTURE-ULTRASONIC PROPERTY RELATIONSHIPS IN STEELS

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**Abstract:** Microstructural characterization by ultrasonic measurements and effect of microstructural phases on the ultrasonic properties were studied on AISI/SAE 1040 and 4140 steels. By rapid cooling and isothermal heat treatments, the specimens having martensite, tempered martensite, bainite, fine pearlite and coarse pearlite were obtained. Microstructures were characterized by optical and scanning electron microscopy, and hardness tests. Sound velocity and attenuation measurements were performed using the pulse-echo technique. The relationships among sound velocity, sound attenuation, microstructure and hardness were investigated.

**Introduction:**
Controlling the mechanical properties of steel components is important because the they may change considerably even in the same batch, or after application of deformation/heat treatment processes not all parts have to be the same mechanical properties, or faulty heat treatment may change these properties drastically. In order to prove that the properties are the same as the design stage, mainly destructive testing techniques like tensile testing and metallographic inspection are carried out. These traditional methods are performed by cutting a representative sample from the material and performing tests on that sample. However, in some cases precise knowledge of the actual material properties used in the structure should be known, and quality control by sampling may not support the safety requirements. Therefore, determination of the mechanical properties of materials by nondestructive techniques becomes a challenging task.
Papadakis reported a comprehensive set of data on the attenuation and velocity of both longitudinal and transverse waves in hardened and tempered steels as functions of austenitizing temperature and ultrasonic frequency [1]. Klinman, *et. al* proposed to use the ultrasonic attenuation due to grain boundary scattering as proxy for grain size in the well-known Hall-Petch relations [2,3]. Smith *et. al* investigated the effect of varying the carbon content on the microstructure, ultrasonic attenuation, and ductile to brittle transition temperature in a set of high purity, iron-carbon alloys of approximately constant grain size [4]. Kopec and Hanak measured the ultrasonic attenuation in the fine pearlitic steel used for railway wheels. The measurements showed that the contribution of the scattering component can be attributed to grain, grain boundaries, grain distribution, influence of manufacture, content of the ferritic component [5]. Murav'ev investigated the influence of hardening, tempering, and annealing on the velocity of ultrasonic vibrations [6]. Prasad and Kumar have correlated sound velocity and ultrasonic attenuation with the heat-treatment conditions of steel castings [7]. Bouda *et.al* measured sound velocity and attenuation by both longitudinal and transverse wave at the half cylindrical shape Jominy specimens of steel [8]. The aim of this study is to determine the effect of microstructure of steel on sound velocity and ultrasonic attenuation, and to find out a correlation between ultrasonic parameters and hardness of the material, which is directly related to microstructure.

**Experimental:** AISI/SAE 1040 and 4140 steels in the form of hot rolled bars of 30 mm diameter were cut perpendicular to the rolling direction to 5 mm thick specimens, and then, the specimens were ground to obtain appropriate roughness and surface parallelity. Since some differences in grain size and banding have been observed in the initial microstructures, all specimens were water-quenched after austenitizing at

900°C for 0,5 h. As a result, initial microstructures of all specimens became identically martensitic. After austenitization at 850°C for 0,5 h the specimens have been heat treated as shown in Table 1.
In sound velocity measurements a 20 MHz normal beam longitudinal wave probe, Philips-PM3365A pulse generator and Gould Data SYS 740 Digital oscilloscope have been used. Sound velocity was determined by measuring the time taken for the ultrasonic waves to travel through thickness of the material between parallel faces. A constant force is applied to the probe so as to provide a constant thickness of couplant machine oil layer at the probe-specimen interface. For attenuation measurements, 8-10 backwall echo patterns have been obtained using USD 15 equipment and a 15 MHz normal beam probe.
For optical and scanning electron examinations, the specimens were cut into two to observe the microstructure through the thickness. On each specimen, five Vickers hardness values were taken, and then a mean hardness value for each group was determined

Table 1. Heat treatment procedures following austenitization at 850°C for 0,5 h

| No. | AISI / SAE 1040 | AISI / SAE 4140 |
|---|---|---|
| 1 | quenching | |
| 2 | quenching + tempering at 200°C | |
| 3 | quenching + tempering at 600°C | |
| 4 | Salt bath (380°C, 10 min) | |
| 5 | Salt bath (600°C, 10 min) | Salt bath (600°C, 90 min) |
| 6 | Salt bath (680°C, 60 min) | |

**Results and Discussion:** Almost identical microstructures were observed throughout the thickness of the samples. Fig.1a and 2a show the martensitic structure. Tempering at 200°C did not change the microstructure considerably (Fig.1b,2b). By tempering at 600°C clear changes were observed in the martensite (Fig.1c,2c). Bainitic structure was obtained successfully in AISI/SAE 4140 specimen (Fig.2d). However, in the AISI/SAE 1040 specimen 100 % bainite could not be obtained since as the nose of the IT – curve is very close to zero on time line; i.e., the microstructure of consists of bainite and pearlite (Fig.1d). Aim of the last two heat treatments is to obtain pearlitic structures having different interlamellar spacing. Fig.1e and 2e shows fine pearlite, and Fig.1f and 2f shows the coarse pearlite. Some proeutectoid ferrite also exist (max. 50% under equilibrium cooling condition).

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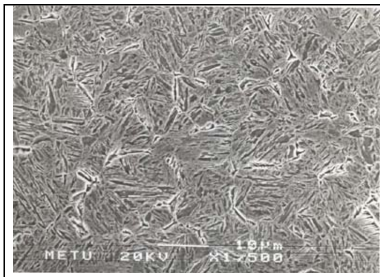
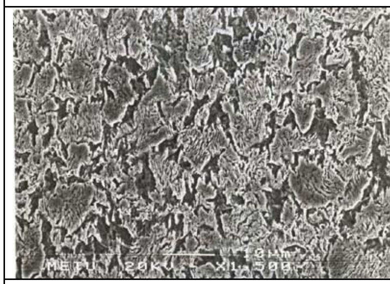
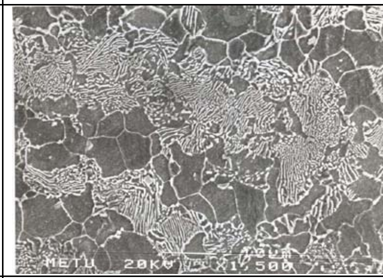
|  |  |  |
| a) martensite | b) tempered martensite, 200°C | c) tempered martensite, 600°C |
|  |  |  |
| d) bainite + pearlite | e) ferrite + fine pearlite | f) ferrite + coarse pearlite |

Figure 1. Microstructures of heat treated AISI/SAE 1040 specimens

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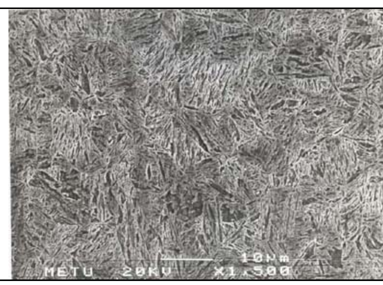
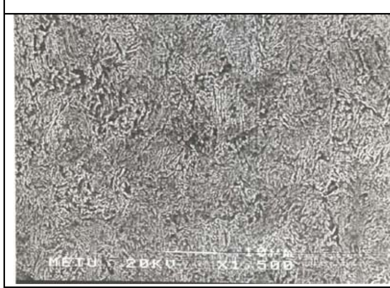
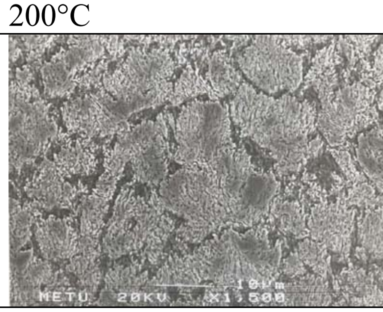
|  |  |  |
| a) martensite | b) tempered martensite, 200°C | c) tempered martensite, 600°C |
|  |  |  |
| d) bainite | e) ferrite + fine pearlite | f) ferrite + coarse pearlite |

Figure 2. Microstructures of heat treated AISI/SAE 4140 specimens

Hardness measurements can be used as a direct indicator of the phases obtained. The microstructure having the highest hardness is martensite (658 HV for 1040, 674 HV for 4140). By tempering, hardness of martensite drops dependent on tempering temperature. While hardness of martensite tempered at 200°C reduces slightly (575 HV for 1040, 636 HV for 4140), tempering at 600°C reduced the hardness significantly (282 HV for 1040, 386 HV for 4140). Hardness of the bainitic microstructure is 238 HV for 1040 and 330 HV for 4140. Hardness value of ferrite–fine pearlite is 208 HV for 1040, 270 HV for 4140. That of ferrite–coarse pearlite is 178 HV for 1040 and 199 HV for 4140.

An inverse relationship between sound velocity and hardness were observed. For instance, the microstructure having the highest hardness, i.e., is martensite, has the lowest velocity.

It is known that sound velocity is affected by both grain size and microstructure. It has been stated that an increase in grain boundary area, which means decrease in grain size, results in large scattering of ultrasonic waves which causes ultrasonic waves to take a longer path to cover the material thickness, which decreases the sound velocity drastically [9].

In this study, in order to be able to determine only the effect of phases on sound velocity, the average grain size tried to be kept constant. Before the isothermal heat treatments, all the specimens have been austenized and quenched in water following the same procedure to obtain martensitic structure, next for various isothermal treatments, each specimen has been austenized at 850°C for 0,5 h. Then, the isothermal heat treatments have been performed leading to the desired microstructure. Thus, the average size of austenite grains of all specimens maintained constant, ensuring the only parameter affecting the ultrasonic measurement to be the differing microstructures.

As seen in Fig.3, martensitic structure is the one having the lowest velocity. It has been reported that sound velocity decreases due to the increase in dislocation density and lattice distortions [9-11]. Martensite, which is formed by diffusionless shear transformation, contains dislocation density as much as the material which is hardly cold worked ($10^{11}$ - $10^{12}$). It can be concluded that the reason for the lowest sound velocity for martensite is its high dislocation density. It has been stated that residual stresses may also be considered as a reason for decrease in sound velocity [12]. Due to high dislocation density, micro residual stresses remain in the martensitic structure. Comparing the volume changes during phase transformations it is clear that the microstructure having the highest residual stress, due to volume change and dislocation density, is martensite.

Tempering of martensite resulted in an increase in the sound velocity. After tempering at 200°C, sound velocity increased very slightly compared to martensite. During tempering, the dissolved carbon precipitates into carbides. This is associated with a decrease of the specific volume of martensite and complete relief of micro residual stresses. Together with this, partial loss of tetragonality and very small drop of dislocation density seem to be the reasons of the velocity increase. Tempering at 600°C resulted in a marked reduction in dislocation density, which directly reduces micro residual stresses. Those combined with the changes in the morphology of the microstructure result in a remarkable increase in the sound velocity.

Bainitic transformation is virtually identical to martensitic transformation, and an increase in the dislocation density has been observed [13]. However, it grows at relatively high temperatures. Since the residual stress and misorientation of bainite is less than those of martensite, it is reasonable to expect that the sound velocity of bainite should be higher. The sound velocity of bainite is higher than that of martensite tempered at 200°C; however, lower than the one tempered at 600°C. Since tempering at 200°C did not produce considerable differences either at microstructure or sound velocity, obtaining a higher sound velocity for bainite is reasonable. On the other hand, by tempering at 600°C a new microstructure is produced: dislocation density decreased sharply, martensite lost its tetragonality, cementite appeared in the structure, and spheroidized. In the case of AISI/SAE 1040 steel, since the microstructure consists of bainite and pearlite, the results do not show the same tendency as AISI/SAE 4140 steel. Sound velocity of AISI/SAE 1040 steel for bainitic microstructure is higher than that of martensite tempered at 600°C.

For both steels, sound velocity of ferrite–coarse pearlite have been found higher than that of ferrite–fine pearlite due to the higher lamellae spacing, higher ferrite content and thicker ferrite size of coarse pearlite.

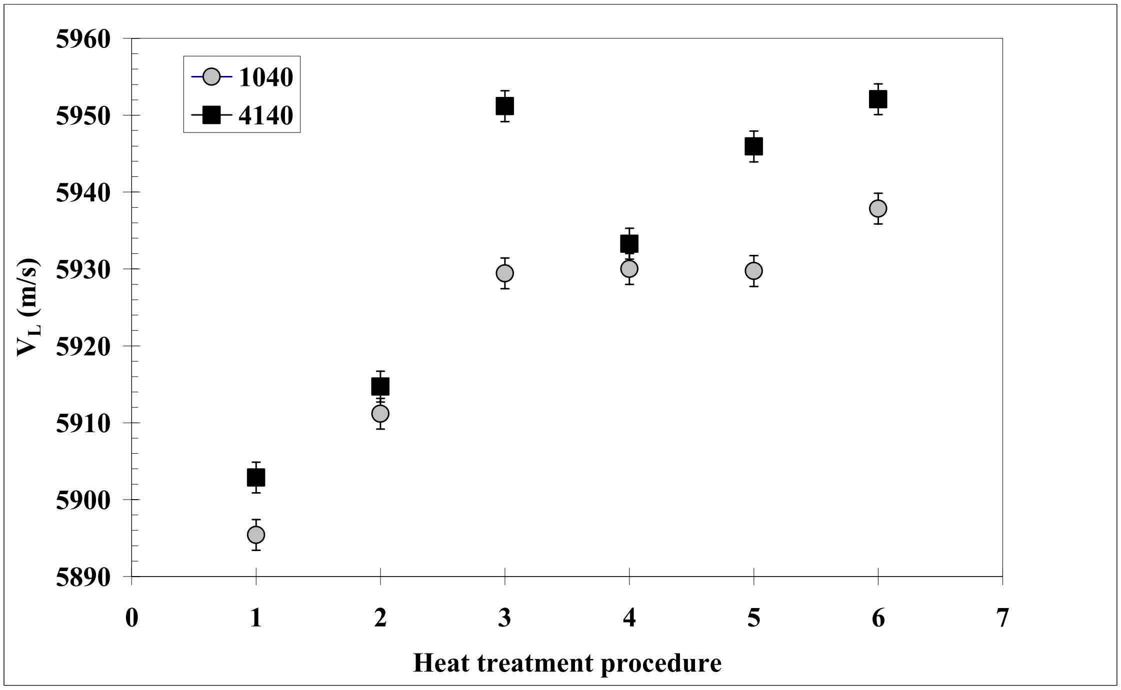



Figure 3. Effect of microstructure on the sound velocity of AISI/SAE 1040 and 4140 steels (1:M, 2:Temp-M 200$^o$C, 3:Temp-M 600$^o$C, 4:Bainite, 5:Fine-P, 6:Coarse-P)

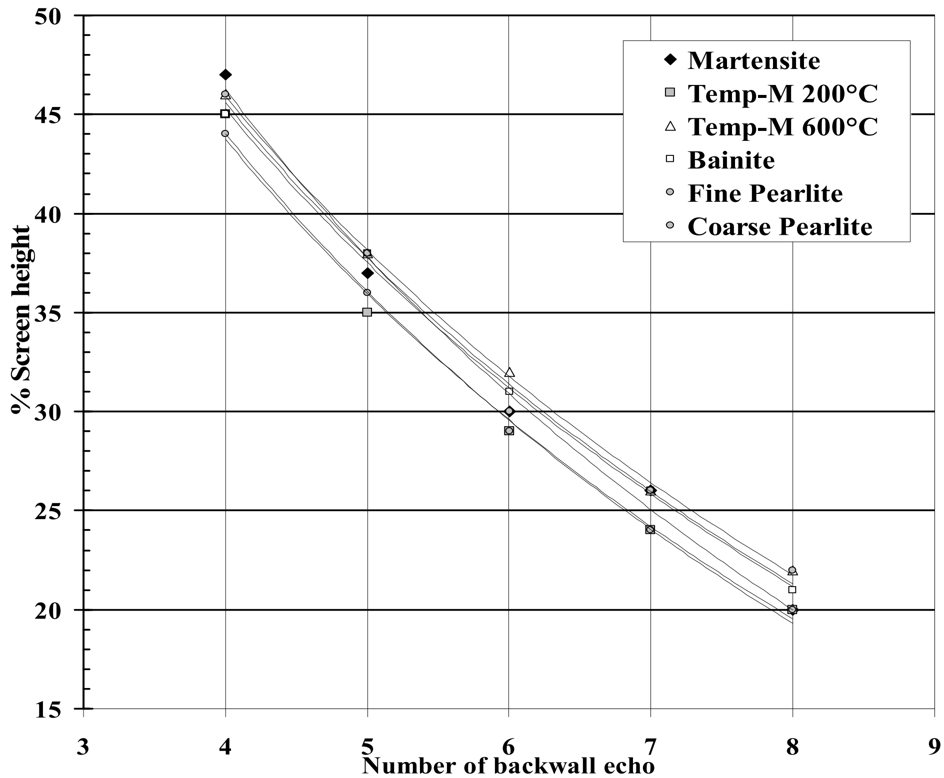



Figure 4. Effect of microstructure on the backwall echo pattern of AISI/SAE 1040 and 4140 steels

The backwall echo patterns of microstructures are very close to each other, i.e., within the error limits. Although there seems to be a correlation between microstructures and backwall echo patterns, to make generalization requires further research (Fig.4). To obtain the desired phases uniformly throughout the samples, the specimens were prepared as thin as possible, and probably although echoes ranging from 5 to 8 are chosen for comparison of backwall echo heights, it could not be enough to produce attenuation differences between microstructures. However, in general it can be said that the most attenuating phases are martensite and ferrite-coarse pearlite, and the least attenuating phases are bainite and martensite tempered at 600°C. The martensitic hardening introduces a very high dislocation density, causing greater absorption of sonic energy [11,12]. The attenuation is greater in the case of samples having larger area of interface and softer microstructure than in the case of samples having smaller area of interface and harder microstructure. Such a matrix is able to absorb more sound energy, which is ferrite-coarse pearlite, hence the attenuation in the case of samples having larger area of interface is greater than the case of samples smaller area of interface.

**Conclusions:** Sound velocity is directly influenced by the microstructural phases of steel. It is minimum in martensite due to increased dislocation density and residual stress, and increases with the following sequence: bainite, ferrite-fine pearlite, ferrite-coarse pearlite. Tempering of martensite results in an increase in ultrasonic velocity, which is dedicated on the tempering temperature. Tempering of martensite at 200°C slightly increases the sound velocity because of small microstructural changes. However, tempering at 600°C changes martensite drastically and ultrasonic velocity increases considerably.

There is an inverse relationship between ultrasonic velocity and hardness of the heat treated steel specimens. Microstructure having the highest hardness is the one having the lowest ultrasonic velocity and vice versa.
Although there seems to be a correlation between microstructures and backwall echo patterns, most of the results are within the error limits to make generalization requires further research. However, it was observed that the most attenuating phases are martensite and coarse pearlite, and the least attenuating phases are bainite and martensite tempered at 600°C.

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