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Influence of Local Mechanical Properties of High Strength Steel from Large Size Forged Ingot on Ultrasonic Wave Velocities

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Abstract. In the metallurgical industry, ultrasonic inspection is routinely used for the detection of defects. For the non-destructive inspection of small high strength steel parts, the material can be considered isotropic. However, when the size of the parts under inspection is large, the isotropic material hypothesis does not necessarily hold. The aim of this study is to investigate the effect of the variation in mechanical properties such as grain size, Young's modulus, Poissons ratio, chemical composition on longitudinal and transversal ultrasonic wave velocities. A 2 cm thick slice cut from a 40-ton bainitic steel ingot that was forged and heat treated was divided into 875 parallelepiped samples of 2x4x7 cm^3. A metallurgical study has been performed to identify the phase and measure the grain size. Ultrasonic velocity measurements at 2.25 MHz for longitudinal and transversal waves were performed. The original location of the parallelepiped samples in the large forged ingot, and the measured velocities were used to produce an ultrasonic velocity map. Using a local isotropy assumption as well as the local density of the parallelepiped samples calculated from the chemical composition of the ingot provided by a previously published study, Youngs modulus and Poissons ratio were calculated from the longitudinal and transversal wave velocities. Micro-tensile test was used to validate Youngs modulus obtained by the ultrasonic wave velocity and an excellent agreement was observed.

INTRODUCTION

Ultrasonic wave propagation in materials such as steel is well understood because of the development in ultrasonic non-destructive testing (NDT). Ultrasonic NDT is routinely used in the primary metal manufacturing industry to detect various types of defects [1]. In some cases, steel is elaborated to have specific thermo-mechanical properties in order to target an application. Consequently, the composition and the treatments are combined to obtain the desired properties. For small volumes ingots, cast methods, forging and heat treatment are well known and mastered [2][3]. However, for large-sized ingots, various complications may occur due to their large dimensions [4]. For example, during quenching treatment, the core temperature is always higher than the rest of the ingot. This affects the cooling rate and the physical properties of the steel. It is possible to have an ingot with a martensitic predominant component at the surface with a tetragonal-centered structure (TC), whereas the center will mainly be bainite and pearlite with a centered cubic (CC) structure [5]. Other modifications can be induced during the forging process, macrosegregation and heating can impact final mechanical properties of the ingot [6]. The aim of this study is to analyse the influence of the mechanical and metallurgical parameters on the propagation of ultrasonic longitudinal and transversal waves. Youngs modulus, Poisson ratio, density, grain size, and microstructure will be considered and analysed.

MATERIALS

The material used for this experiment was a medium carbon low alloy steel with the nominal composition of Fe-0.35C-0.99Mn-0.5Ni-1.86Cr-0.149V (wt.%). After casting and solidification, the block was forged in a parallelepiped

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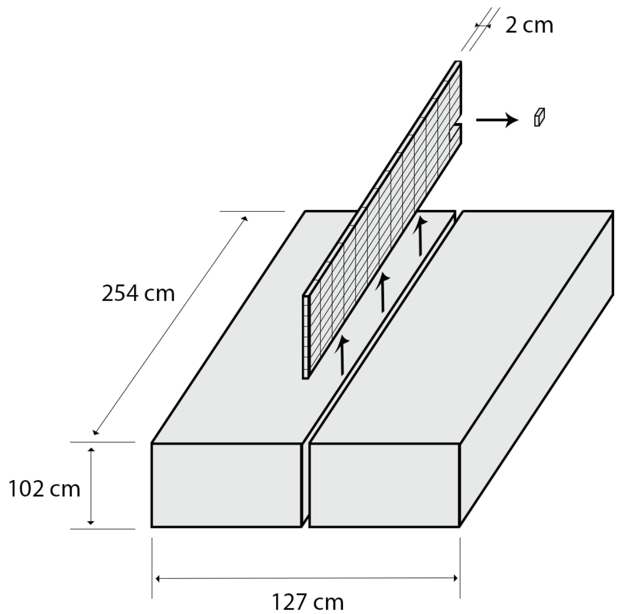

FIGURE 1. Caste ingot cut in a 2cm thick slice then divided in 875 samples

shape to reach the dimensions of 102x127x254 cm^3. After this process, it was heat treated with a quench and a tempering. Then, the 40-ton ingot was cut following its longitudinal axis in a 2 cm thick slice which was finally divided into 875 parallelepipedic samples of 2x4x7 cm^3 that will be used in this study (Fig. 1).

The knowledge of the properties and the elaboration of this type of large steel ingot represents a major challenge to the manufacturers. Their aim is to manufacture blocks that are homogeneous and with no flaws above a critical size. Many factors can influence the final result. First, while casting and during the solidification process, the metal is in its liquid form. This phenomenon generates chemicals heterogeneities due to the large size of the ingot. The cause of this heterogeneity is related to the movement of the liquid during the solidification. During freezing, some elements have a lower solubility in the solid than in the liquid phase. This leads to a continual enrichment of the liquid in those elements and a lower solute concentration in the primary solid (Fig. 2). A recent chemical composition study [4] of the ingot used in this study revealed two regions of positive and negative macrosegregation. This previous publication also showed that the C and Cr concentrations were the most dominant in the macrosegregation. It also appeared that the macrosegregation only had a small impact on the microstructure type and the hardness properties. The second important parameter of the elaboration of this type of ingot is the grain size. The block was forged in an open die forging process, quenched and tempered. The first treatment was a mechanical treatment that reduces the volume of the ingot and the size of the grain. A previous study gave a prediction method of the grain size for open die forging that was tested on an ingot forged from 700 mm to 500 mm diameter [7]. The result showed that the real-time measurement of the temperature was an important parameter for the grain size prediction. However, an excellent correlation between model and the experimental data was found. This study confirmed that the grain size after forging is expected to be lower than 70 μm. In this study, the ingot was forged following the same process and then quenched to stop the grain growth induced by the high temperature. Finally, a tempering is applied to homogenise the block and release the strength. During tempering, the size of the ingot has a strong impact because the convection takes more time relative to a small volume ingot. The core temperature stays higher than the surface temperature such that the microstructure of the material is modified. This phenomenon induces a longer tempering at the core in comparison to the surface. It is then possible to expect grain size to grow and mechanical parameters to be modified.

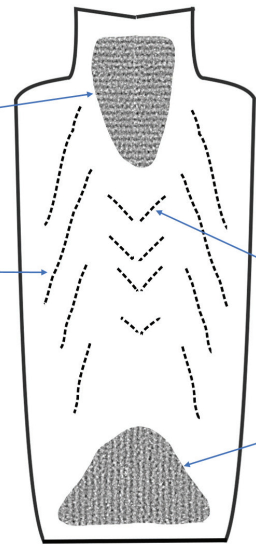

FIGURE 2. Schematic representation of segregation map in steel with positive and negative segregation.

PROPAGATION OF ULTRASONIC WAVES IN STEEL

Ultrasonic NDT is commonly used in the steel manufacturing industry. This method is popular for its capacity to characterise the material without affecting its properties. In most inspections, transducers are used to detect cracks and other flaws. Some recent studies have shown that more information could be extracted from those measurements. For example, the attenuation of ultrasonic waves is related to the grain size in austenitic phase [8]. This method enables the measure in real-time of the grain growth by laser-ultrasound. Another study from Young [9] showed that the attenuation coefficient of ultrasonic wave was a function of the heat treatment of the material (quenched, tempered, post weld heat treatment). It was therefore possible to predict the fracture appearance transition using the ultrasound measurements. Finally, another study investigated the velocity of ultrasonic waves in austenitic stainless steel. This work done by Palanichamy [10] proposed a method to estimate grain size in this type material. It showed an excellent correlation between grain sizes determined by wave velocity measurement compared with the metallography estimation, especially for shear waves.

METHOD

As detailed in the previously section, the NDT characterisation of the different parameters like grain size or microstructure of ingots represents an important issue for the steel industry. In the present case, the block was chemically heterogeneous due to its macrosegregation; the grain size was expected to vary between the core and the surface and the phase was supposed to vary from martensitic to bainite. Samples were taken following the depth symmetrically to the vertical axis of the ingot at two different heights. The aim of this study is to observe the variations depending on the depth, the position of the macro-segregation and confirm the assumed symmetry axis of the ingots. The selected samples are shown on the ingot schematic in Fig. 3.

Measurements are made in pulse-echo mode using 2.25 MHz longitudinal and shear transducers. The time of flight was determined by cross-correlation of two back wall reflections. The dimension of the block was cut to a precision of ±0.01 mm for a thickness machined of 38.9mm. This variation represents an uncertainty of $\pm 3.5 m.s^{-1}$ on the velocity measurement. On the other hand, the difficulty was to avoid the presence of border effects due to the small dimensions of the samples. Indeed reflections from other modes appeared in the measurement. For this reason, a modal identification was performed using CIVA simulation software. The entire set of samples was measured under the same temperature and humidity conditions in order to minimise the variation of external factors. The measurement campaign was repeated three times to confirm the repeatability.

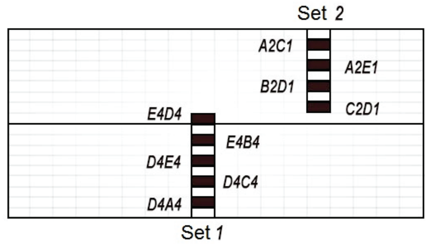

FIGURE 3. Samples selection from the slice (Fig. 1)

VELOCITIES MEASUREMENTS

The results of longitudinal and shear velocity measurement are provided in Fig 4.

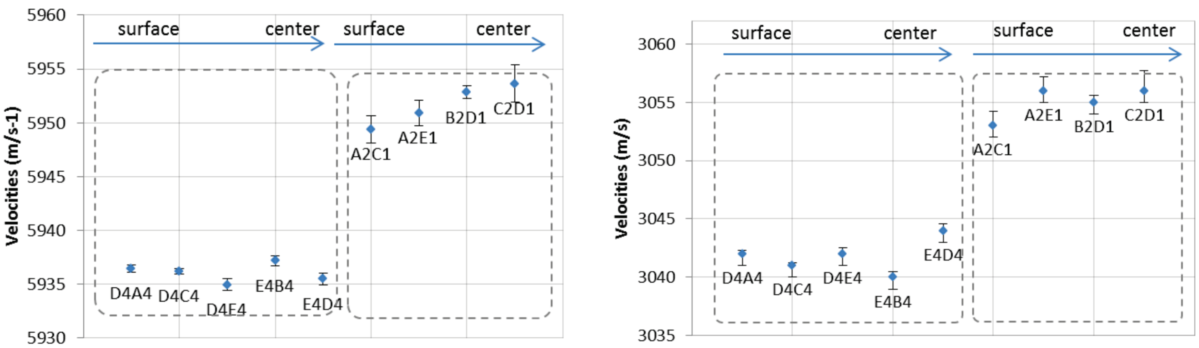

FIGURE 4. Velocities measurements (a) Longitudinal waves (b) Shear waves

Firstly, it is possible to see that errors linked to standard deviation are very low. In the set 1, velocities are close with a variation of less than 3 m/s that is the measurement uncertainty. In set 2, there is a global growth but the most notable information is the gap between the sets. In order to explain those variations, the phase, and the grain size were determined with metallurgical studies, the chemical composition was analyzed, and mechanical parameters like Young Modulus were measured by micro tensile tests.

METALLURGICAL STUDY

The metallurgical study was made on samples used for ultrasonic velocity measurements. The two samples presented in figure 5, were taken at different depth in the ingot; one near the surface and the other one in the center of the ingot.

The composition was around 99% of bainite and 1% of austenite. The metallographic study revealed that the grain size varied between 70 μm at the surface to more than 700 μm at the core of the ingot. The results were similar for both sets of samples, such that the velocity gap could not be explained by a grain difference. This result were confirmed by the work S. M. Chentouf [11] on the same block.

From 5 it is also possible to note that no significant variation can be observed between samples from a given set. As previously demonstrated, the grain size was mainly a function of the depth; this implied that ultrasonic wave velocity did not depend on the grain size in bainitic steel and that the block can be considered homogeneous along its transverse axis.

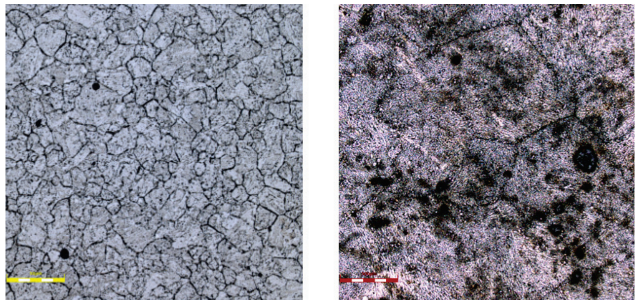

FIGURE 5. Metallographic of some samples (a) sample from the surface (b) sample from the core

INFLUENCE OF DENSITY

Considering that the material was locally homogeneous and isotropic with Young modulus and Poisson ratio constant, the equations below can be used to calculate empirical density from chemical composition:

$$V_L = \sqrt{\frac{E(1-\ )}{\rho(1+\ )(1-2)}} \qquad\qquad V_T = \sqrt{\frac{E}{2\rho(1+\ )}} \tag{1}$$

Considering that Young's and Poisson's ratio are constant, they are isolated in a global variable supposed constant such that the velocity of the longitudinal wave become a function of the density. Thanks to a previous study from our team [11] the composition of the 875 samples was measured and its possible to compare it to the theoretical composition given by the datasheet. Fig 6 represents the carbon concentration:

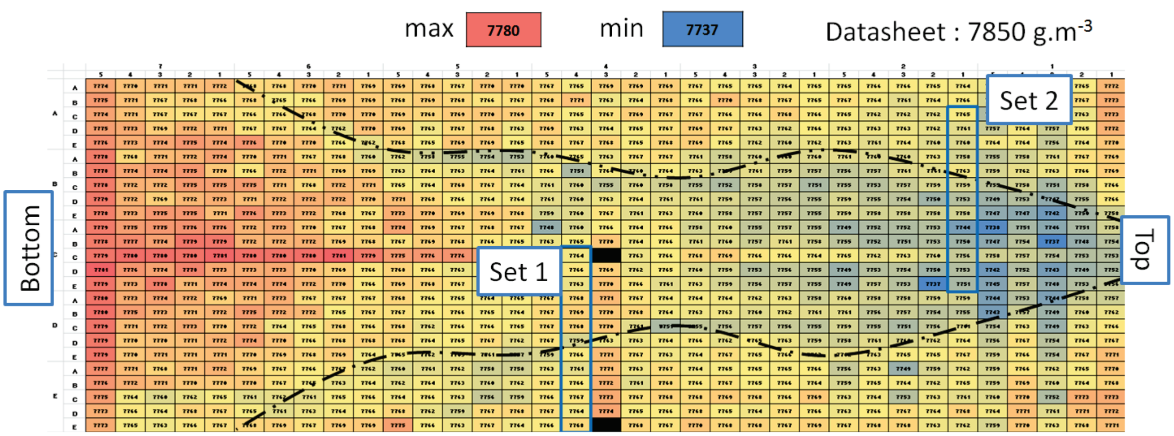

FIGURE 6. Density map of ingot using chemical composition

This map confirms that the chemical heterogeneity linked to macro segregation exists. The first observation is that density is different from datasheet value. It is also possible to see that the density remains almost equal in set 1 whereas in set 2 density decreases from the surface to the center. Associating those measurements and the formula 51 for the literature [12], local empirical density can be found:

$$\rho = 7875.96 - 0.2970T - 5.6210^{-5}T^2 + (-206.35 + 0.00778T + 1.47210^{-6}T^2)C_c +$$
$$(-8.58 + 1.22910^{-3}T + 0.85210^{-7}T^2 + 0.018367C_{cr})C_{cr} + (-0.22 + 0.4710^{-3}T \quad (2)$$
$$-1.85510^{-3}T - 1.85510^{-7}T^2 + 0.104608C_{ni})C_{ni} - 36.86C_{si} - 7.24C_{mn} + 30.7C_{mo}$$

It is then possible to calculate the velocities using empirical density calculated from the chemical composition. Comparisons with the ultrasonic measurements are provided in Fig 7 for longitudinal and shear waves.

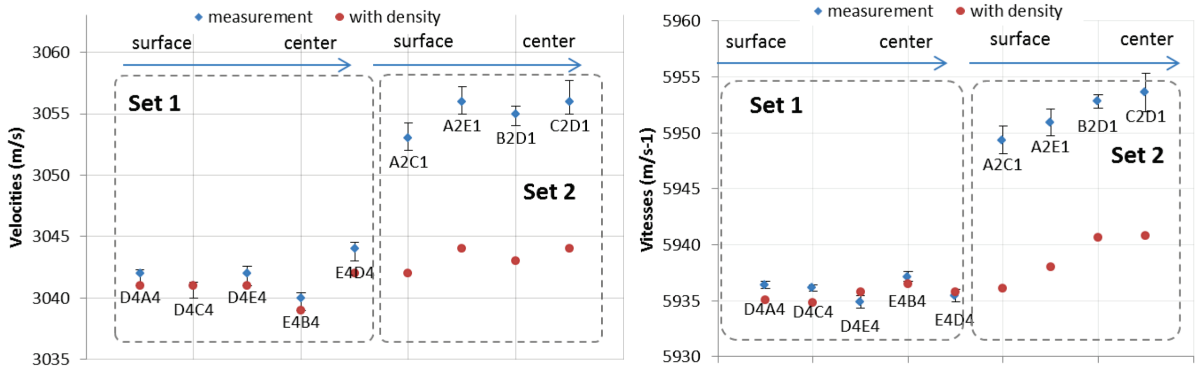

FIGURE 7. Comparison of the measurements and empirical values of shear velocities calculated from chemical compositions

As seen in Fig. 7 the trend is respected for the samples from the same set, but the gap of 10 m/s between the two groups cannot be explained by the density calculated using the empirical chemical composition. It is therefore possible to say that the chemical composition affects ultrasonic measurement but in this case, it is not possible to use the homogeneous hypothesis. By deduction, the hypothesis saying that Young's modulus and Poisson's rfation are constant is wrong. From the previous equations, using the density obtained from the empirical chemical composition, a system of 2 equations and 2 unknowns is obtained. By solving the system, it is possible to find estimate of Young's modulus and Poisson's ratio. In order to identify which parameter can explain the velocity gap between the sets the velocities are first calculated while maintaining Poisson's ratio constant. The calculation is then repeated but with a constant Young's modulus.

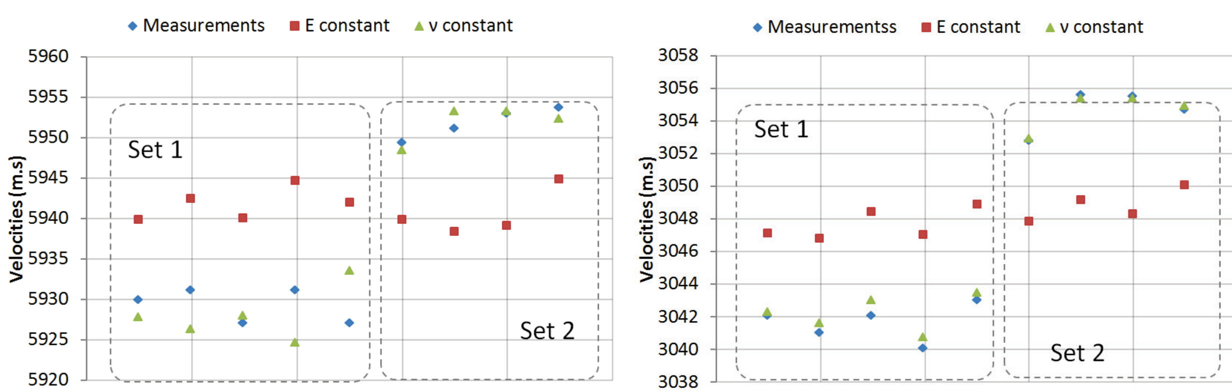

FIGURE 8. Study of the impact of Young and Poisson coefficient on shear velocities

As it is possible to see in Fig. 8 when the Young's modulus was constant, the calculated velocities did not agree with the experimental measurements. Whereas when the Poisson's was constant, an excellent agreement was observed. From those observations, it is possible to say that the Young's modulus was the parameter that dominates the evolution of the longitudinal and transversal velocities whereas the Poisson's ratio had minimal impact.

TENSILE TEST

To confirm this important results micro tensile tests were performed on the samples and the Young's modulus measured was compared to the values calculated by solving the previous system of equtions with densities calculated from chemical composition. The samples were the same that were used for ultrasonic measurements. For confidentiality reasons, results are given in percentage and can be found in Fig. 9.

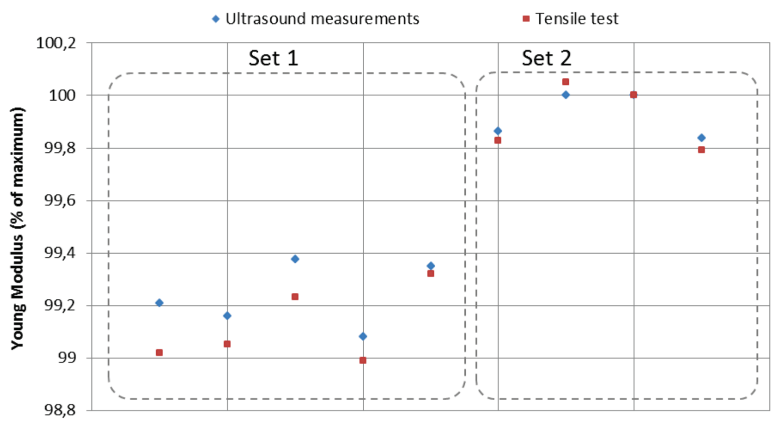

FIGURE 9. Comparison of Young Modulus from micro-tensile test and ultrasonic measurements with empirical density

An excellent agreement was observed so those measurements confirmed the values found using empirical data and ultrasonic velocities. The hypothesis that the Young's modulus was responsible for the velocity gap was confirmed.

CONCLUSION

This study has shown that the velocity appears to be independent of grain size in large size forged ingot of high strength steel mostly composed of bainitic steel. Indeed, no significant variation was observed between the samples from the surface to the core of the ingot. The metallographic study revealed that the grain size varied from 70 μm at the surface to more than 700 μm at the core. This paper then showed that density measured from the chemical composition only lightly influenced the ultrasonic bulk velocities. However, the major player on ultrasonic bulk velocities was identified as the Young's modulus. The variation of Young's modulus observed in the ultrasonic velocities was confirmed by micro-tensile testing.

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