LU 2008 Laser Ultrasonics, Montréal

1st International Symposium on Laser Ultrasonics: Science, Technology and Applications
July 16-18 2008, Montreal, Canada

Alteration of the Elastic Properties of Steel and Cast Iron Caused by Hardening

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Abstract

Generally, the elastic material properties (e.g. Young's modulus and Poisson ratio) in steel and cast iron are assumed to be unaffected by hardening processes in common literature. Only the hardness is presumed to alter, while the elastic properties keep constant. As the results of traditional and FEM (finite element method) static and dynamic stress calculations directly depend on the accuracy of these properties - they are highly crucial.

We show that the elastic properties get considerably modified during the hardening process. The change in Young's modulus was up to 4%. An increase in hardness was associated with a decrease of the Young's modulus. This effect was measured in steel alloys, as well as in cast iron.

Measurements were performed utilizing a picosecond-laser and a photorefractive interferometer. Subsequently, the elastic properties were calculated from the recorded signals and the known density of the materials. As the measurements are performed contactless, future measurements will be done during the hardening process to get more detailed information on the recrystallization processes in solids and the associated change of the elastic parameters.

Keywords: Laser ultrasound, mechanical characterization, Young's modulus, hardening, carbon steel

1. Introduction

The exact knowledge of the elastic properties is very important for static and dynamic stress calculations of mechanical structures. Accurate values lead to safer and mostly also lighter constructions. Usually, the used values are based on measurements done on non-hardened, feritic-pearlitic carbon type steel. It is presumed that the elastic properties don't change after the hardening process.

In this paper we will show measurements performed with our LUS (Laser Ultrasound Setup [1, 2]) and by dynamic mechanical analysis on feritic-pearlitic and martensitic carbon steel types and present variations of the elastic properties caused by different microstructure types.

The presented values are calculated by means of sound velocity measurements.

As LUS is contactless and to a certain point non-destructive it can further be used not only in the lab, but also as quality control for microstructure testing.

This method also promises to solve another problem: during fabrication of alloy steel the alloy materials can vary to a certain extent. Thereby the sound velocities and further the elastic properties are modified, which can also be analysed.

2. Experiments

2.1 Laser Ultrasound

LUS (Laser Ultrasonic Setup) consists of Nd:YAG type generation laser, with a pulse length of 20ps and a wavelength of 1064nm. The generation laser was focussed to a line to generate directive acoustic waves. This leads to low generation energy with high signal to noise ratio. The energy was set to 10mJ which resulted in usable signal to noise ratio and low destruction of the surface [3, 4].
The detection was achieved with a detector from Bossa Nova Tech which consists of an interferometer with a photorefractive crystal and a 532nm Nd:YAG laser. The laser was focussed to a spot on the specimen surface. Both detection and generation took place on the same side of the specimen in reflexion measurement scheme. During measurement the generation line was laterally adjusted in direction to the detection point (Fig. 1).

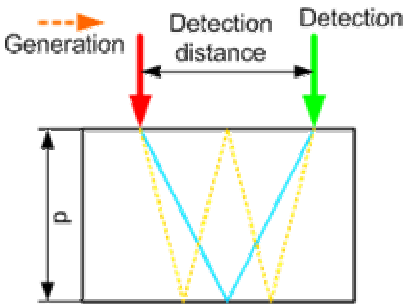

Figure 1. Measurement Setup. During measurement the generation was moved along the surface towards the detection point. The yellow and blue lines mark the first and second echoes of bulk waves.

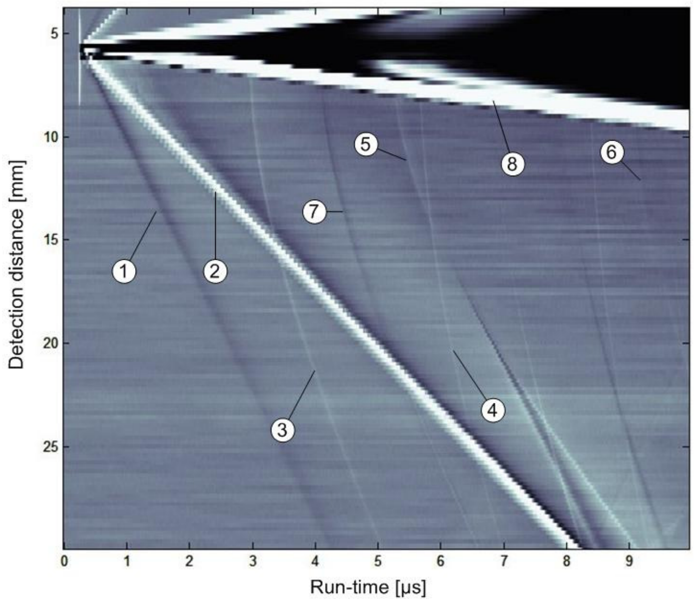

Figure 2. Measurement results. The marks indicate the following waves: 1 direct longitudinal wave, 2 Rayleigh wave, 3 first longitudinal wave, 4 second longitudinal wave, 5 first transversal wave, 6 second transversal wave, 7 mode converted wave and as mark 8 the air pressure wave.

Figure 2 shows the measurement result. Different wave curves are well defined and can be easily distinguished. Via curve fitting and by knowledge of the exact thickness *d* the velocities are obtained. The sound velocities of the longitudinal wave V_l and the transversal wave V_t lead to the elastic properties Poisson ratio μ, Shear modulus G and Young's modulus E [5]:

$$\mu = \frac{\frac{1}{2} - (\frac{V_t}{V_l})^2}{1 - (\frac{V_t}{V_l})^2} \qquad (1)$$

$$G = \rho \cdot V_t^2 \qquad (2)$$

$$E = 2 \cdot G \cdot (1 + \mu) \quad (3)$$

An approximation of the Rayleigh wave velocity V_R was calculated from the sound velocities V_l and V_t by [6]:

$$K = \frac{\mu}{1-\mu} \quad (4)$$

$$V_R \cong V_t \cdot \sqrt{\frac{0{,}44+K}{0{,}58+K}} \quad (5)$$

2.2 Dynamic mechanical analysis

The DMA (Dynamic Mechanical Analysis) was performed with a 3-point bending setup. On the specimen a sinusoidal deformation was applied with an amplitude of 40µm and a frequency of 1Hz. For the measurement the specimens had to be prepared to exact dimensions which was done by WEDM (Wire Electrical Discharge Machining) (Fig. 3). This machining method was chosen as WEDM is supposed to maintain the microstructure of the specimens.

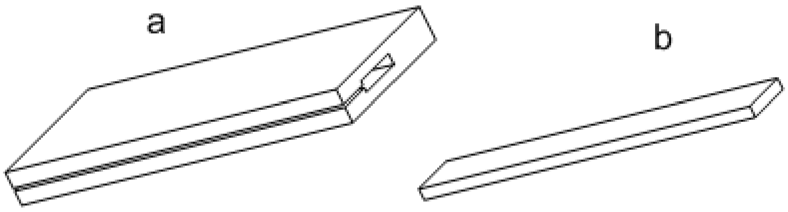

Figure 3. Specimen a) was tested with LUS. Specimen b) for dynamic mechanical analysis was extracted after LUS measurements.

3. Results and Discussions

Two different types of carbon alloy steel, 42CrMo4 and 38MnVS5, and a cast iron sample, GGG70, were analysed. To detect variations by induction hardening process the specimens were taken from the same charge in ferritic-pearlitic microstructure. One sample of each carbon alloy steel type was transformed to martensitic structure by induction hardening. Before the hardening process the specimens were annealed to apply smoother microstructure, relax the internal stresses and to recover cold work which can lead to anisotropic elastic properties. It is assumed that the induction hardening process changed the microstructure of the whole volume homogeneously.
The densities ρ were calculated from volume and weight measurements and are further used to derive the elastic properties in equation (2).
Table 1 shows the results obtained by the LUS measurements and the calculated elastic properties Poisson ratio μ, Shear modulus G and Young's modulus E.
The measurement results show a decrease of the sound velocities and an increase of the Poisson ratio after the hardening process. As the Young's modulus and Shear modulus depend on the sound velocities and linearly on the density ρ (equations 1 to 3) they show a decrease after hardening.

Table 1. LUS measurement results

	Hardness (HRC)	ρ	V_l	V_t	$V_{rayl.}$	Poiss.ratio	Shear mod.	Young's mod.
		kg/m^3	m/s	m/s	m/s		GPa	GPa
38MnVS5 ferritic	56	7685	5944	3255	3012	0,2858	81,4	209,4
38MnVS5 mart.		7685	5929	3242	3001	0,2867	80,8	207,9
42CrMo4 ferrit	56	7747	5989	3264	3023	0,2887	82,5	212,7
42CrMo4 mart.		7747	5900	3210	2981	0,2898	79,8	205,9
GGG70 ferrit		7246	5756	3113	2885	0,2933	70,2	181,6
GGG70 hardened		7246	5477	3010	2773	0,2836	65,6	168,5

The percentage variations of elastic properties were calculated by the relation $X = \frac{X_{ferrit} - X_{martensit}}{X_{ferrit}} \cdot 100$ where X_{ferrit} is the ferritic elastic property, $X_{martensit}$ the martensitic one and X the percentage of modification. Cast iron GGG70 showed severe ultrasound attenuation, which resulted in high uncertainty of the revealed sound velocities. Therefore the values (e.g. the lowering of Young's modulus of -*7%*) are not further discussed.

The results are plotted in figure 4 where the effects can clearly be seen.

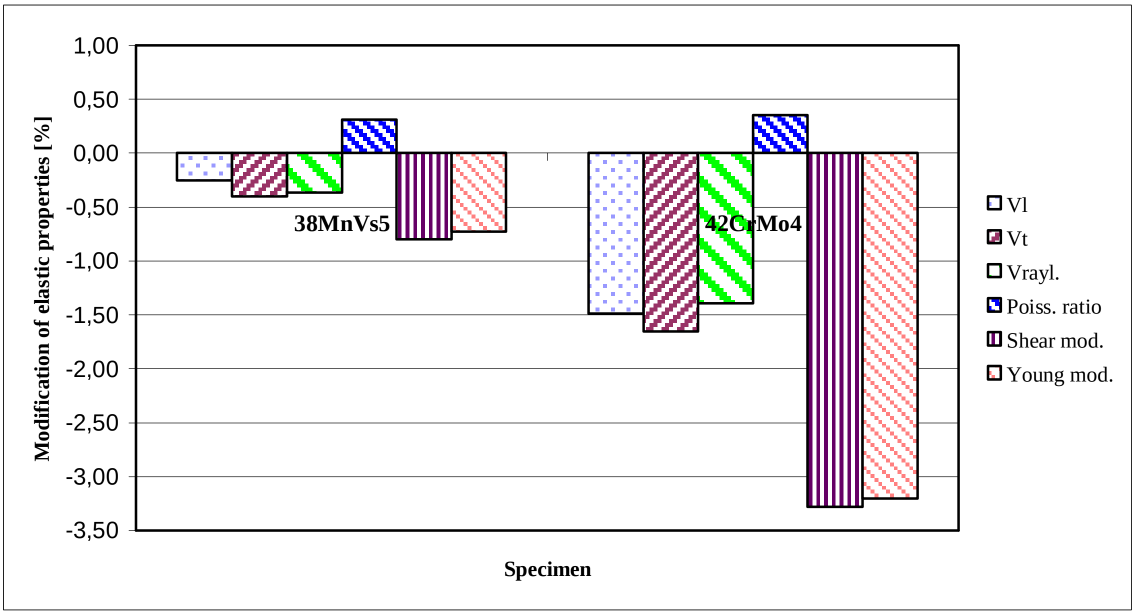

Figure 4. Alteration of the elastic properties by hardening, measured with Laser-Ultrasonic-Setup.

On both carbon steel types the modification of transversal wave velocity was greater than on longitudinal wave velocity, which resulted in an increase of the Poisson ratio by about *0.32%*. The Young's modulus of 38MnVS5 and 42CrMo4 showed a modification of *-0.7%* and *-3.2%*, respectively. These effects were also reported in [7, 8].

Table 2. Dynamic mechanical measurement results

		38MnVS5 ferrit	38MnVS5 mart.	42CrMo4 ferrit	42CrMo4 mart.
Young's mod.	Gpa	205,5	203	203,5	204

The dynamic mechanical analysis of the two carbon alloy steels with a 3-point-bending test is shown in table 2. The change of Young's modulus was clearly shown for 38MnVS5 carbon type steel with a modification of *-1.2%*. The small variation for 42CrMo4 is about the uncertainty of the measurement and is therefore not further considered.

For this measurement small specimens were extracted from the original sample as described in section 2.2. The differences between the results of LUS and DMA may result from the different observed volumes. E.g., the sample could be inhomogeneously hardened, as the outer areas are faster cooled as the inner ones. Also slight changes on the elastic properties by the WEDM method could have occurred and have to be revealed.

Differences on the absolute values of Young's modulus of the non-hardened samples may result from slight errors on the determination of the density ρ.

3. Conclusion and Outlook

We showed with LUS and DMA (only on carbon steel 38MnVS5) that a change of the elastic properties by hardening appeared. The martensitic transformation by induction hardening resulted in a lowering of the sound velocities of the longitudinal wave V_l and transversal wave V_t. Therefore the Shear modulus and the Young's modulus decreased, whereas the Poisson ratio increased. The results are in good relation with previous papers [7, 8].

In future work the homogeneity of the hardness will be tested and variances along the thickness may show up. The results should clear the differences between LUS and DMA measurements.

In an ongoing project measurements will be done during the hardening process in an experimental annealing oven to get more detailed information on the recrystallization processes in solids and the associated change of the elastic parameters. The measurements will investigate changes of bulk wave velocities and also the spectral modifications of SAWs (Surface Acoustic Waves) [9].

Acknowledgements

We want to thank Dr. Cecilia Poletti (Vienna University of Technology) for the dynamic mechanical analysis of the specimens.

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