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Evaluation of micro-damage by acoustic methods

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Abstract

Several methods for the determination of integral damage in sheet metal are reviewed and investigated at the example of the ferritic steel DC04. A novel method to determine damage in cylindrical rings is proposed. Such a method is useful for the measurement of damage in components manufactured by sheet-bulk forming. In sheet-bulk-forming or precision forging sheets with a thickness in the range of 1-5 mm are processed by making use of an intended three-dimensional material flow to form toothed components such as gears. Damage leads to the modification of physical properties, such as Young's modulus and the related resonance frequency. Young's moduli were determined by various methods such as tensile tests and the frequency of natural oscillations of rectangular samples as well as cylindrical rings. Additionally, the change in the propagation velocity of ultrasonic waves in rectangular bars was examined as a damage criterion and reference measurements of damage by electron microscopy were carried out. The damage values obtained by electron microscopy are consistent with the results of the other investigated methods.

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Keywords: Ductile damage; Young's modulus; Resonance frequency; Wave speed; Ultrasound

1. Introduction

The experimental determination of damage in sheet metal parts is crucial to evaluate the success of new forming process strategies or the component performance during lifetime. Damage refers to the degradation of physical properties such as the elastic stiffness, electrical conductivity or mass density due to defects. The defects may include

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non-metallic inclusions, voids or cracks in ductile metals. Micro- and nanoscale damage in metals is usually measured by means of electron microscopy at magnifications within the range of x5.000 to x80.000 or above to resolve even the smallest defects. The integral damage expressed by the damage variable D can be determined by averaging a large number of resource-intensive EM studies in different areas of interest.

Previous studies of the influence of microstructural characteristics, in particular microdamage, on the metal quality may serve as a basis for the development of integral methods for an assessment of the damage level. The effect of damage on the elastic properties is well studied and is considered in constitutive models for the mechanical behaviour [1]. Young's modulus E_{sta} can be measured with satisfying accuracy by means of tensile tests. The variation of this static Young's modulus is studied in [2] at the example of successive tensile deformation samples with an unloading after every tension step. Such method is suited to determine the damage level if the damage is homogeneously distributed over the sample volume. In this case, the damage variable is expressed by Young's moduli of the damaged $\tilde{E}_{stat}$ and undamaged reference sample E_{stat}, respectively [1].

Young's modulus, as well as mass density ρ, determine the properties of a material as an elastic medium. Characteristic resonance frequencies of the samples, as well as characteristics of elastic wave propagation allow identifying Young's moduli. Methods to determine these dynamic Young's moduli E_{dyn} are based either on measurements of the resonance frequency of samples with a basic geometric shape [3], or on wave propagation measurement of high frequency ultrasound waves [4].

The purpose of this work is to evaluate the suitability of several methods to determine the amount of damage in formed components. Therefore, integral damage is determined at the example of a ferritic deep drawing steel DC04 by an acoustic method based on measurements of the propagation speed of ultrasound waves in standard (hexahedral) samples. Moreover, the dynamic Young's moduli, i. e. due to an acoustic excitation, of hexahedral samples and cylindrical rings are measured. The following chapter briefly describes the fundamentals of the acoustic assessment of damage via the method of self-oscillation and the proposed method by a measurement of the propagation of ultrasound waves. In the third chapter the damage values obtained by the acoustic methods are compared with conventionally measured damage values by both mechanical tensile test and electron microscopy.

2. Determination of damage

Commonly used methods (Fig. 1) to measure damage in the steels due to plastic deformation feature different accuracy, complexity and effort [1]. Here, to evaluate and compare damage determined by the methods 2.2, 2.3 and 2.4, we have to examine specimens with different damage states.

Chapter	2.1	2.2	2.3	2.4
Method	**Mechanical loading-unloading of tensile specimen**	**Resonance frequencies of self-oscillating specimen**	**Ultrasonic wave propagation velocity**	**Electron microscopy**
Measuring effect	Softening of static Young's Modulus E_{stat} with increasing damage	Decreasing resonance frequency ν_{pla} and thus E_{dyn} with increasing damage	Decreasing velocity V with increasing damage	Increasing volume fraction of voids with increasing damage
Specimen	Damage progress measurable at one tensile specimen	Specimens with differing states of damage separately measured		

Fig. 1. Overview of various methods to determine integral damage in plastically deformed steels.

2.1. Mechanical loading-unloading of tensile specimen

According to the method proposed by Dufailly and Lemaitre [2], tensile specimens are loaded and unloaded in a universal testing machine. The change in Young's modulus E_{stat} is determined during subsequent unloading steps. Here, the limits of the applied stresses should be in the range of 0.15 to 0.85 of the ultimate tensile strength of the material.

2.2. Self-oscillations of plates and rings

The evaluation of the wave equation with the principle of virtual velocities for a loose rod with constant cross-section [4, 5] yields an expression for the dependency of dynamic Young's modulus E_{dyn} on the geometry (in terms of length l and thickness d), the mass density ρ, and the resonance frequency of self-oscillations ν_{Pla} of plates:

$$E_{dyn} = \frac{48\pi^2}{m^4} \cdot \rho \frac{l^4}{d^2} \nu_{\mathrm{pla}}^{2}\,, \tag{1}$$

where m = 4.7300408 represents the Madelung constant. It is assumed that $l << d$. Eq. 1 is valid for the transverse oscillation. The standing wave required for self-oscillation is supported in two points with 22.418% distance from the rods ends [5]. This fact imposes certain limitations on the geometrical dimensions of the plates such as the sample length to obtain stable oscillations and is limiting the possibilities of acoustic methods with low and medium frequencies.

In Eq. (1) the connection between E_{dyn} and ν_{Pla}^2 is linear. Therefore, we can conclude that the influence of micro-damage in the plate on dynamic Young's modulus and correspondingly on the self-oscillation resonance frequency is locally additive. In other words, the integral damage can be determined in ductile metal plates with a homogeneous distribution of damage based on the integral changes in elastic properties.

To overcome the limitations on the frequency imposed by the geometry, in particular the size of the specimens, characteristics of the propagation of ultrasound waves can be applied (cf. section 2.3). The relation between the frequencies of self-oscillations of the plates and the specimen length is depicted in Fig. 2(a). Here, low-carbon steel plates, which were long-term annealed at a temperature of 250 °C (E_{stat} = 200 GPa) with a density of ρ = 7800 kg/m^3 were investigated. As experience has shown, the most convenient frequencies of self-oscillation for measurements are within the range of 300-1500 Hz. Thus, to determine the dynamic Young's modulus, it is convenient to use 1-3 mm thick plates with a length of 60-200 mm. The use of samples with a length of less than 50 mm results in a high increase of the frequency of self-oscillations for the mentioned thicknesses (Fig. 2). For plates less than 30 mm the frequencies of self-oscillation are in the ultrasonic range. This requires the application of other methods to determine the level of integral damage.

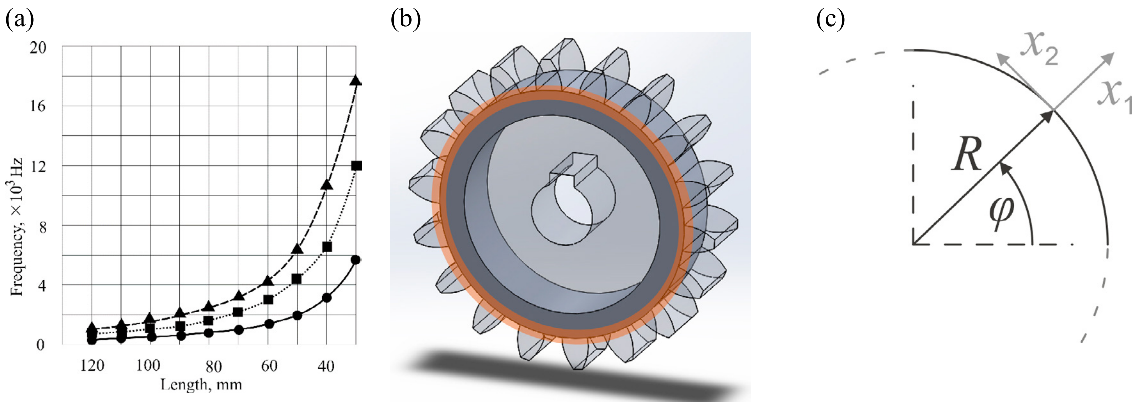

Fig. 2. (a) Dependency of frequencies of unconstrained transverse vibrations (self-oscillations) on length of plate with thickness of ● 1 mm, ■ 2 mm, ▲ 3 mm in the interval of 250 Hz to 16,000 Hz; (b) Sketch of ring-shaped sample which can be prepared from gear manufactured by sheet-bulk metal forming; (c) Coordinate system applied to describe ring geometries from (b).

Regarding samples of small dimensions, a self-oscillation of the sample can only be obtained in the region of high oscillation frequencies. The smaller the length of the sample along the x-axis and the smaller its thickness, the higher the self-oscillation frequency (cf. Fig. 2(a)). The applicability of the method of self-oscillation was reported in [6] at the example of damage coefficients measured by both electron microscopy and self-oscillation experiments for deformations of up to 10% with respect to an annealed reference material [6]; previous studies showed that low temperature annealing does not lead to noticeable changes in the texture of such steel sheets [15].

Metal forming parts feature shapes much more complex than the investigated hexahedral bodies. One example for sheet-bulk metal formed parts are gears, see Fig. 2(b) [6]. Gears or sections of gears can be idealized as cylindrical rings (see small highlighted color dark ring on the front Fig. 2(b)) with different external and internal diameter respectively (Fig. 3(a)). For a ring with a constant profile, the coordinates of the point of the middle axis are defined by the radius R of the centre line, the position of the elementary volume which is fixed by the angular coordinate φ, the movement along the ring with the peripheral coordinate x_1 and the radial coordinate x_2 (cf. Fig. 2(c)).

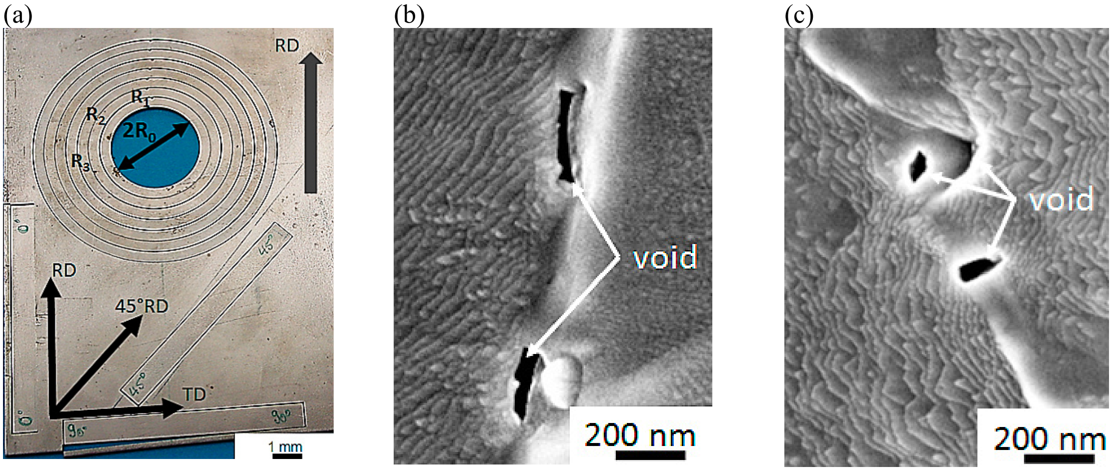

Fig. 3. Use of annular samples; (a) Scheme for cutting plates and ring-shaped samples for experiments; (b) Microstructure of steel DC04 in initial state (delivery status); (c) After long-term annealing at temperature of 275 °C for 48 hours.

The equation of motion in these components takes into account the condition of inextensibility of the centre line and has the form [7]:

$$\frac{\partial^6 x_2}{\partial \varphi^6} + 2\frac{\partial^4 x_2}{\partial \varphi^4} + \frac{\partial^2 x_2}{\partial \varphi^2} + \frac{m_0 R^4}{EI} \cdot \frac{\partial^2}{\partial t^2}\left(\frac{\partial^2 x_2}{\partial \varphi^2} - x^2\right) = 0, \quad (2)$$

which includes only a single variable x_2; here, I is the moment of inertia of the ring section and t the wave propagation time. For a ring the boundary conditions are periodic conditions [8] and the following equation for the resonance frequency of self-oscillations of rings ν_{rin} is obtained:

$$\nu_{\mathrm{rin}} = \frac{6}{\sqrt{5}}\sqrt{\frac{EI}{m_0 R^4}}\,, \quad (3)$$

with m_0 as the mass per unit of thickness of the ring. The damage, according to the Lemaitre criterion [1], will take the form:

$$D = 1 - \frac{\widetilde{\nu_{\mathrm{rin}}}^2}{\nu_{\mathrm{rin}}^2}\,, \quad (4)$$

with $\widetilde{\nu_{\mathrm{rin}}}$ as the self-oscillation frequency of a damaged metal ring. Here, as in the case for the plates, dynamic Young's modulus of the elastic ring material is linked to the self-oscillation frequency ν_{rin} as discussed before in Eq. 1 [9]:

$$E_{dyn} \sim {\nu_{rin}}^2\,. \quad (5)$$

2.3. Propagation of ultrasound waves in damaged structures

(Dynamic) Young's modulus depends on the microstructure itself and on its changes [10]. E. g., in [11] a relationship is established between the propagation speed of surface ultrasonic waves and the impact strength and hardness of hot-rolled steel sheets of a low carbon steel (0.09% C, 1.32% Mn, 0.64% Si, 0.02% P, 0.027% S, 0.02%

Cr, 0.02% Ni, 0.05% Cu). Surface acoustic waves (Rayleigh waves) with a frequency of 1 MHz were applied. A large number of further works are devoted to the study of the propagation of ultrasonic waves in objects in the stress-strain state [12].

If the structure of the metal remains unchanged, then for plates of different sizes with the same geometry the propagation speed of sound waves depends on the amount of micro-damage [10], which is generated and accumulated e. g. in processes of thermal and mechanical treatment and during the life time cycle of components.

The magnitude of this damage can be estimated by Eq. (6):

$$D = 1 - \frac{{V_{damage}}^2}{{V_{init}}^2} \quad , \tag{6}$$

with the propagation speed of sound waves in the damaged metal V_{damage} and the propagation speed of sound waves in the undamaged metal V_{init}.

A decrease of the speed of longitudinal and surface ultrasonic waves due to the occurrence of microvoids in the process of creep and fatigue tests was observed in [13-15].

From the published data for steels follows that the more the structure is stressed, the lower the propagation speed of ultrasound waves. When steel is tempered, internal stresses are removed by reducing the defect density and the state of the metal is moved towards a state of balance. This results in an increase of the magnitude of Young's modulus [6, 15] and accordingly to an increase of the propagation speed of ultrasound waves. The authors of [6] showed, that the value of the propagation speed of ultrasound waves for various types of thermomechanical processed specimens varies within the range of 0-2%. Such changes can easily be measured by modern ultrasonic equipment. E. g. in [11], the accuracy was estimated as 0.003-0.005%. Here, the accuracy of measuring the propagation speed of ultrasonic waves can be increased by randomizing systematic errors due to large measurement statistics.

Modern ultrasonic reflection detectors, apart from detecting large defects in form of cracks, voids, etc., are equipped with suited software to accurately measure the propagation speed of ultrasonic waves in samples of various shapes.

2.4. Electron microscopy investigations

Applied to the study of micro- and nano-damage, the method of ion slope cutting [17] of surfaces of steel samples can reveal the presence of a noticeable number of micro- and nano-voids and other similar discontinuities in the material in the cross section of the sheets. Based on the area fraction of voids per observed region of interest the void volume fraction per material volume can be calculated to determine a damage value.

3. Research and results

The material investigated were sheets of the low-carbon steel 1.0338 (DC04) (0.06% C, up to 0.35% Mn, up to 0.40% Si,~0.025% SiP), thickness 2 mm. Segments of 300 mm x 200 mm were cut. A part of these segments was processed with long-term annealing at a temperature of 275 °C for 48 hours to obtain sheets with a structure approximate to balance (reference state), since the as-delivered cold-rolled material has undergone considerable thermo-mechanical treatment. The annealing is supposed to cure or close defects such as voids, which are present due to the process history of the cold-rolled material. The annealing temperature was chosen from the following consideration. The measurement of dynamic Young's modulus showed that samples annealed at such temperature in the region of 225-300 °C (pre-crystallization) feature a Young's modulus, which is the largest in all directions of measurement and practically does not change in this temperature range. At higher annealing temperatures, it is possible to increase the Young's modulus in some directions. However, this is accompanied by the development of a texture due to recrystallization and other structural changes. Therefore, the structure of the annealed samples can be considered quasi-balanced and can be used as a reference state with a reduced damage level.

The aim of the investigations was to explore novel methods to determine damage both in

- non-plate-like structures (rings) by acoustic methods via self-oscillation and
- structures of small dimensions by wave propagation velocities in the ultrasound range (Fig. 4).

For reference, the following methods were used as well: mechanical testing, acoustic method in the human-audible range at the example of plates and electron microscopy.

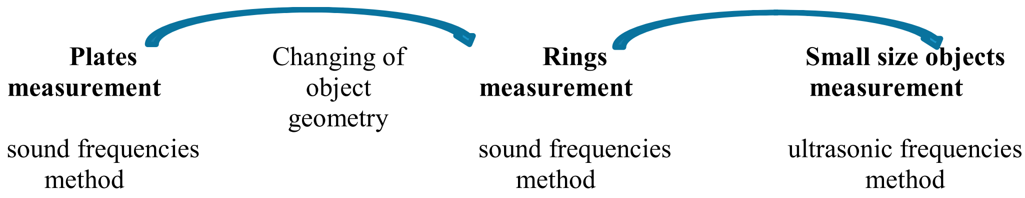

Fig. 4. Diagram of acoustic methods for determination of integral damage in deformed steels.

a) Mechanical loading-unloading tensile tests

As described in section 2.1, tensile specimens were loaded and unloaded in a universal testing machine Zwick Z100 (100kN), type 0.5, with deviations in measuring of the tensile force less than 0.5%. Samples for mechanical testing were cut out in the rolling direction (RD) from samples in the states as-delivered (initial) and annealed in accordance with the standard DIN 50125 Form H and EN ISO 6892-1. The length of the working part for mechanical testing was 50 mm, the width 12.5 mm. The unloading was started after reaching a tensile stress of 175 MPa in accordance with the recommendations in [2]. Averaged over three specimens the values of static Young's moduli E_{stat}^{ini} and E_{stat}^{anl} of the samples, which were cut in RD from the initial and annealed sheets of steel, were 193.8 and 198.8 GPa, respectively.

b) Acoustic method based on the frequency of self-oscillations

In addition to rectangular plates with a length of 120 mm and 12 mm width, ring samples of various diameters were prepared (cf. Fig. 3(a)). The oscillations of the flat samples were excited by a slight impact with a graphite rod. The flat samples were placed on prisms of a wooden resonator, observing the condition of the arrangement of the nodes of oscillation (4) [6]. For precise support in the nodes of the standing wave, one of the prisms was moved by means of a screw with a thread pitch of 0.5 mm [6]. Samples in form of rings were hung on strings and excited by a slight impact with a graphite rod on the outer diameter of the ring. It should be noted that the samples of these sizes gave a clear and stable sound. The frequency of natural oscillations was measured using the "Spectra PLUS" software. The results of the frequency measurements of rectangular plates and rings are presented in Table 1. The values of the dynamic Young's moduli in the state of delivery were 216.1 GPa and after long-term annealing 219.3 GPa. Thus, the dynamic Young's moduli are approximately 10% higher than the static ones determined by the tensile tests.

c) Acoustic method based on the propagation speed of sound waves

For this study, two direct piezoelectric transducers for sending a wave and for recording the reflected wave were used. Recommended frequencies of ultrasonic waves for metals lie in the range of 1-50 MHz [1]. In this case, a series of oscillations is formed due to sequential reflections of the probing pulse from the opposite surfaces of the sample (Fig. 3(a)). It is possible to use piezoelectric transducers, emitting both longitudinal and transverse ultrasonic waves. In order to assess the magnitude of the interference distortion of reflection, the delay time of the first [t_1], second [t_2] and third [t_3] reflection were measured. The differences in time were in sufficient consent towards time measurement errors. The determination of these errors was made by means of multiple measurements of the transit time of ultrasonic waves at different points of the sample input (10-12 measurements). Furthermore, a statistical processing of the measurement results was carried out using the standard procedure in the confidence interval of 0.5%.

The change in the speed of propagation of the ultrasound wave after annealing demonstrates the dependence of the propagation velocity of waves on the level of micro damages. Taking into account the direct proportional relationship between E_{dyn}, the frequency of natural oscillations of the samples and the propagation speed of ultrasound, damages were calculated by this method. The results of the propagation speed measurements with a frequency of 2 MHz and the value of D, which was measured, are presented in Table 1.

d) Electron microscopy method

Additionally, representative areas were investigated by on electron microscopy to determine the amount of damage in the initial samples as well as the annealed samples by the method of Lemaitre [1]. Fig. 3(b) and (c) reveal the differences in micro and nano scale damage for the investigated material stats. In the annealed samples noticeable damage was observed at the grain boundary only, but almost no damage was visible inside the grains. In contrast, damage in the as-delivered state (initial) was significantly higher. Here, voids of greater volume and amount were present at the grain boundaries as well as a huge amount of nano voids inside the grains. Quantitative estimation of the ratio of voids volume to the allocated representative volume for different sections of the deformed sheet relatively to annealed samples gives values in the range of 0.02-0.06 for different observation sections of the sheets. Hence, the results of acoustic measurements are in good agreement with the results of electron microscopy

Table 1. Comparison of results for various applied methods.

method	**mechanical tensile tests**		**resonance (plates)**		**resonance (rings)**		**wave propagation**		**electron microscopy**	
measu-rand	Young's modulus (static)		self-oscillation frequency				sound speed		void volume or area per region of interest (volume or area)	
symbol	E_{stat}		ν_{pla}		ν_{rin}		V		S	
unit	GPa		Hz		Hz		m/s		µm² or µm³	
material states	initial vs. annealed								initial (=damaged)	
relation	$E_{initial} / E_{annealed}$		$\nu_{initial} / \nu_{annealed}$				$V_{initial} / V_{annealed}$		$S_{damaged} / S_{total}$	
values	193.8	198.8	740.3	751.7	481.7	488.0	5775	5925	1248.4	1296.1
damage	$D = 1- E_i / E_A$		$D = 1- \nu_i / \nu_A$				$D = 1- V_i / V_A$		$D = 1- S_d / S_t$	
damage value	**0.04**		**0.03**		**0.025**		**0.05**		**0.02 - 0.06**	

Comparison of the different methods reveals that the level of the integral damage *D* of the deformed metal, relative to annealed samples, can be assessed from the change in the elastic modulus measured by static and dynamic methods and by measuring the change in the propagation speed of ultrasonic waves.

4. Conclusions

- The value *D*, which was measured in state of delivery of steel sheets DC04 by the method of the static Young's modulus, was 0.04. By measuring the natural frequencies of plates and rings values of 0.03 and 0.025 were determined. Calculation of the damage coefficient, based on the results of the change in the propagation speed of ultrasonic pulses, gave a result equal to 0.05. A direct method for determining the coefficient *D* by means of electron microscopy (differential damage, "in situ") takes into account the ratio of the damaged areas and total cross-sectional area of the sample, which gives a result in the range of 0.02-0.06 for different sections of the samples. The values of the integral *D* determined by electron microscopy are within the limits of scattering of the differential *D*.
- Acoustic methods for assessing the damage in deformed materials are applicable to objects of both flat form (sheet) and products in the form of disks and rings, while the use of static methods for estimating the Young's modulus is difficult for the later.
- The application of acoustic methods of high frequencies waves gives the opportunity to decrease the size of the investigated objects.

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