APPLICATION OF NON-DESTRUCTIVE ULTRASOUND STRUCTUROSCOPY TO STRENGTH DETERMINATION OF DEEP-DRAWING STEELS

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Abstract: *The impulse for creation of this contribution was exploration of new possibilities in the field of application of non-destructive ultrasound structuroscopy of thin sheets. The tested samples were made from material that can be ranged to group of IF steels by its chemical composition and mechanical properties. These materials are directly used to bodywork stampings manufacturing. The checking of mechanical properties using static tensile test, which is continually on regular basis used for this purpose, was made at first. The resulting values were compared with enclosed normatives and their guaranted properties were evaluated. The acoustic paths (thicknesses) of tested samples were measured using ultrasound instrument and ultrasound probe to obtain informations about ultrasound velocity in transradiated material. The aim is to find and describe new opportunities useable for non-destructive determination of mechanical properties of these steels using obtained mathematical models.*

Key-words: DEEP-DRAWING STEELS, STATIC TENSILE TEST, ULTRASOUND STRUCTUROSCOPY, ULTRASOUND VELOCITY

1. Introduction

Since nowadays the increasing requirements and claims are put on finished products quality, it is necessary to deal with new possibilities, those could help to achieve these requirements and intentions.

The attention will be focused on field of serial production of bodywork stamps. The new verification possibilities of supplied materials mechanical properties will be searched for automotive parts which are typical by their irregular shape and seriousness for quality and manufacturing technology. The physical properties of tested samples shall be measured using ultrasound instrument at first. The mathematical dependencies shall be determined using regression analysis methods those shall serve to determination of basic mechanical property like the tensile strength is. The static tensile test, that is continually on regular basis used for this purpose, shall be used for destructively determined strength.

The aim shall be the verification of this method application possibility to thin sheet mechanical properties determination just in ienvironment of serial production of bodywork stamps.

2. The investigated materials – IF steels

The materials which belong to group of IF steels by their chemical composition and mechanical properties were taken to as-performed experiment (interstitials free steels, see Table 1.). These materials are commonly used for automotive body building. They ownes interstitially dissolvable carbon and nitrogen atoms bound in stable carbonitrides (TiCN, NbCN) obtained by microalloying by Nb or Ti or else by combination of Nb and Ti. The considerable improvement of plastic properties of steels can be reached by decreasing of carbon and nitrogen content in the state of solid solution. Steels with various Nb and Ti content are continually developed to achieve optimum between strength and workability of sheet. The practical tests show that alloying by Nb or by combination of Nb and Ti is more favourable. Naturally, the Nb amount has effect on grain size, ageing of steel and increases recrystallizing temperature as well. The consequence of it is higher energy consumption at production (higher annealing temperatures). The resulting mechanical properties depends on content of other alloying elements causing solution strengthening (e.g. Mn, P), amount and dispersity of precipitates, size of ferrite grain and also on draught at smooth rolling. This draught has very considerable effect on workability, since it is performed in cold state. The IF steels are microalloyed by group of other elements or a small amount of phosphorus for solid solution strengthening achievement in order to mechanical properties enhancement [1].

3. Tensile test

The test by uniaxial tension is basic test which is used for evaluation of material mechanical properties. This test is based on deformation of testing bar by uniaxial tensile loading, usually up to breaking in order to determine one or more material stress and strain characteristics. It is performed at room temperature usually. Rate of loading varies from 0,5 to 2,0 mm min^{-1}. Testing of metallic materials in Czech Republic are followed by standard ČSN EN 10002. [2]

Table 1. Example of chemical composition IF steel

C [ppm]	N [ppm]	P [ppm]	S [%]	Mn [%]	Al [%]	Ti [%]	Nb [%] + Ti [%]
15	**25**	**60**	**50**	**0,12**	**0,03**	**0,05**	**0,02 + 0,01**

Tensile test equipment

The electronic testing machine Zwick Z030 was used for experiments in this work. The nominal force of machine is 30 kN. The adjustable moving rate of moving crosshead is from 0,001 to 200 mmmin^{-1}. The as-measured date are recorded using Zwick testXpert software.

4. Ultrasound structuroscopy

Basic principle of non-destructive ultrasound structuroscopy is experimental determination of mathematical relation (model), that characterizes mutual connection between ultrasound waves velocity (damping) and structure of investigated material (mechanical property). It si concerned with theory of interaction between ultrasound waves and boundary in material, where is possible to find mutual correlation between ultrasound waves velocity and structure, rather mechanical property of material.

The ultrasound waves velocity depends on damping size in transradiated material. It means that its value shall differ in case of steels, cast irons, polymers or composites.

Thus the ultrasound waves velocity sinks with increasing damping of matrix mass and especially with amount and size of internal discontinuities. The discontinuities are reinforcements, layers, inclusions with considerably different wave resistance Z against matrix. [3]

$$Z = c \cdot \rho \qquad [\text{MPa/s}] \qquad (1)$$

The fraction R of reflected pressure of acoustic wave back from boudary increasis with increasing difference of acoustic resistances Z_m a Z_g. $Z_m = 5{,}92 \cdot 7{,}8 = 46{,}2$ MPa/s is valid for steel matrix. $Z_g = 2 \cdot 2 = 4$ MPa/s is valid approximately for carbon in the shape of graphite. $R = (Z_g - Z_m)/(Z_g + Z_m) = 0{,}805$ after inserting. One boundary matrix – graphite so reflects R = 80,5% of pressure of acoustic wave. Direct propagation of acoustic wave through composite is after several reflections from formations of reinforcement consumed and dispersed. Path size of acoustic wave in matrix depends on labyrinth of path through matrix. The value of acoustic path L_u increases in comparison with direct path (thickness of transradiated wall) L with decreasing thickness of formations. Thus ultrasound velocity c_L sinks.

$$c_L = c_{L0} \cdot \frac{L}{L_u} = 5920 \cdot \frac{L}{L_u} \qquad \text{[m/s]} \qquad (2)$$

c_{L0}... ultrasound velocity in steel (etalon for setting of ultrasound instrument).

Boundary character expresses oneself on phase of reflected wave. The boundary with lesser wave impedancy reflects wave in opposite phase than boundary with higher impedancy. This effect if often used in fibrous or layered systems of materials. The highest stair of structure diagnostics is created by spectral analysis of acoustic response (echos, noise). The damping of acoustic oscillations α increases considerably, if wavelength λ approaches to size of reinforcement d. [1.]

$$\propto = k_{\propto} \cdot \lambda \cdot \left(\frac{c_L}{\lambda}\right)^2 \qquad \text{[dB/mm]} \qquad (3)$$

Value α = 0,05 for steel enables to transradiate even meter thicknesses of walls. Non-metallic reinforcement in metallic matrix increases the damping considerably. It achieves α values of higher order, it limits acoustic diagnostics heavily. The ultrasound measurements of austenite steels and graphite cast irons are complicated by austenite gran boundaries and cast iron graphite. The low frequency probes upto 2MHz are necessary for measuring of wall thickness over 30 mm. If the reinforcement by its dimensions d<<l , wave damping reaches acceptable values. Good supposition for ultrasound diagnostics of nanocomposites. The steel owns length of longitudinal wave 1,2 mm, polymers, water cca 0,3 mm for most common ultrasound frequency 5 MHz. E value depends directly on size of sound velocity c_L.

$$c_L = \left\{\frac{\frac{E}{\rho} \cdot (1-\mu)}{1+\mu \cdot (1-2 \cdot \mu)}\right\}^{0,5} \qquad \text{[m/s]} \qquad (4)$$

The simplified expression is used in practice

$$E = \left(K \cdot \frac{L}{L_u}\right)^2 \qquad \text{[MPa]} \qquad (5)$$

…where K is measured on slender cylindrical sample. Ultrasound structure diagnostics requires parallel planes of walls in site of checking. The value of measured L_u is increased by surface roughness (amount of binding medium (c_L 1500m/s in the interspace under probe) and „V“ effect of ultrasound probe on thin walls, so that checking of walls upto L 10mm is inaccurate.

As an example, I can introduce mathematical models formulated for graphie cast irons (connection of ultrasound and magnetic methods of non-destructive structuroscopy), thus for macro-composite with boundary steel matrix – graphite. The formula (6) is calculation of strength in tension R_m and second one is hardness. [4]

$$R_m = C \cdot \left(\frac{L}{L_u}\right)^D \cdot HB^E \qquad \text{[MPa]} \qquad (6)$$

$$HB = A \cdot M + B \qquad \text{[-]} \qquad (7)$$

…where L – actual material thickness, Lu – acoustic path, M – remanent magnetism, A ÷ E constants

5. Experimental

The non-proportionate testing bar with variable wide were use for measurement of sheet mechanical properties in this part of work. It is concerned with testing bars for thin products (sheets, bands and flat products) with thickness from 0,1 mm to 3 mm. The set of 9 specimens was made from tested material. Those testing specimens were made perpendiculary to direction of rolling of as-tested material. The produced testing specimens were submited to static tensile test (ČSN EN 10002) and resulting values are treated in undermentioned Table 2.

Table 2. Finally values obtained by tensile test

90° n = 9	S_0 [mm^2]	E [kN/mm^2]	$R_{p\ 0,2}$ [N/mm^2]	R_m [N/mm^2]	A_g [%]	A_{80} [%]	n [-]	r [-]
$\bar{\chi}$	15,19	203	168	279	25,8	44,3	0,236	2,28
min.	15,19	196	167	278	278	43,2	0,236	2,23
max.	15,19	210	169	279	279	46,3	0,237	2,33
s	0	6	1	0,4	0,2	1,1	0,001	0,04

The measurement of acoustic path L_u using ultrasound instrument (see Figure 1) and 20 MHz probe was performed on each specimen and also strength was measured by destructive method. The courses of single tensile tests are illustrated in Figure 2.

Fig. 1. Used ultrasound instrument

Table 3. As-measured values

Notation	Path Lu [mm]	Actual thickness L [mm]	L/Lu [mm]	UT velocity [m/s]	Tensile strength R_m [MPa]
1	0,73	0,67	0,918	5575,7	279
2	0,73	0,67	0,918	5575,7	279
3	0,74	0,69	0,932	5664,5	279
4	0,73	0,67	0,918	5575,7	279
5	0,74	0,68	0,919	5582,4	279
6	0,73	0,69	0,945	5742,1	279
7	0,73	0,68	0,932	5658,9	279
8	0,73	0,68	0,932	5658,9	278
9	0,73	0,67	0,918	5575,7	278

6. Conclusion

Materials taken for experiments were materials which are suitable for working of deep-drawing bodywork stampings after their properties. Mechanical properties of these tested specimens were determined and checked at first. The resulting values were compared with corresponding normatives which are specified for particular batch of material. It is possible to say on basis of resulting values and course of strengthening curve, that this material corresponds to guarented data given by this steel manufacturer (see Figure 2).

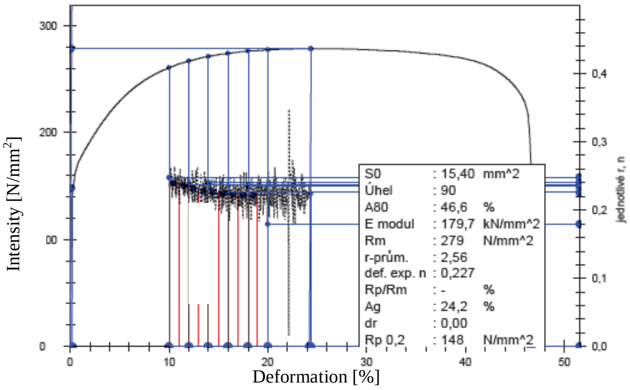

Fig. 2. Graphic course of strengthening curve

Attention was focused on utilization and determination of tested material strength using ultrasound measurement in the second part of this experiment. The graph of dependence between ultrasound velocity and destructively obtained strength is depicted in Figure 4. The as-measured vales are interlined by linear connecting line of trend.

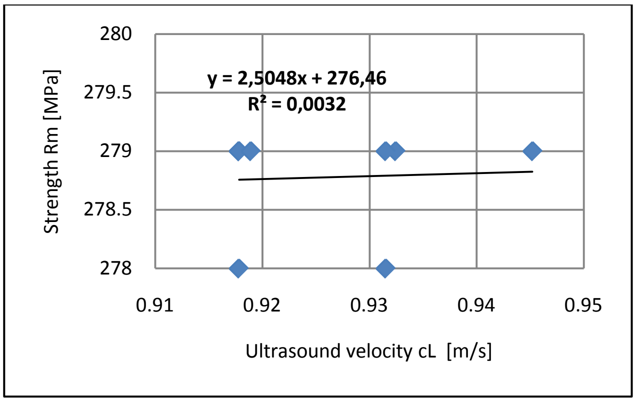

Fig. 3. Graph of dependence between c_L and R_m

Unfortunately we found out that thin samples of sheets and their as-measured values are not ideal for this experiment. The resulting mathematical model and its reliability is insignificant for us. The more wide scatter of measured samples properties is more acceptable to obtain higher reliability of model, which could not be achieved, because it concerned with in the same way thin sheets for which the tracing up the effect of ultrasound wave velocity on structure was difficult.

However this method of ultrasound structuroscopy has applied to other materials as are e.g. graphite cast irons before now, where the reliability of resulting mathematical models (see relation 5, 6) reached up to 98%. Thus it seems to be useful to apply this method for other automotive parts which are made from this material. It should make easy more rapid quality checking, correctness of graphite formations and mechanical properties just on wall of casting without any destructive testing [4].

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