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COMPLEX APPROACH MECHANICAL PROPERTIES AND FORMABILITY ASSESSMENT OF SELECTED DEEP-DRAWING STEELS

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The paper analyses the properties of deep-drawing sheets of three grades (R_e = 320 to 475 MPa), surface-treated with hot-dip galvanizing, made of microalloyed steels. Deformation properties are assessed using tensile tests, technological Erichsen or cupping tests. These characteristics, as well as the behaviour of the surface layer, are also investigated under dynamic conditions (modified Erichsen test using a drop tester), or using flat bending fatigue tests. Using microscopic analysis the deformation properties of the surface layer are evaluated. The results show the compactness of the surface layer, high deformation characteristics, as well as fatigue properties of the investigated deep-drawing materials, suitable for application in the automotive industry.

Key words: deformation properties, fatigue limit, surface layer, technological tests, microalloyed steels

Kompleksni pristup procjeni mehaničkih svojstava i deformabilnosti odabranih čelika za duboko vučenje. Članak utvrđuje svojstva duboko vučenih limova od mikrolegiranih čelika tri kvalitetna stupnja (R_e = 320 do 475 MPa) s površinskom pripremom – toplim pocinčavanjem. Deformacijska svojstva vrednovana su vlačnim pokusom te tehnološkom probom po Erichsen-u, odnosno utiskivanjem. Te karakteristike kao i ocjena površinskog sloja su istražene pri dinamičkim uvjetima (modifikovana proba po Erichsen-u), odnosno pokusi na umor površinskim savijanjem. Mikroskopskim analizama su vrednovana deformacijska svojstva površinskog sloja. Opiti su pokazali na kompaknost površine, visoka deformacijska svojstva, kao i svojstva umora istraživanih dubokovučenih materijala namijenjenih za automobilsku industriju.

Ključne riječi: deformacijska svojstva, granica umora, površinski sloj, tehnološka proba, mikrolegirani čelici

INTRODUCTION

The demands for properties of deep-drawing materials are continuously growing, while new processing technologies and testing procedures to assess the deep-drawing properties are looked for. The formability of materials is influenced by all factors participating in the forming process, namely the sheet material, the product type, the tool and the production technology of a pressing. Indicative information of deep-drawing properties of steel sheets can be obtained from their behaviour during the tensile test. As the pressability criterion, the yield point R_e, the tensile strength R_m, the elongation A, the strain uniform deformation A_g, and the exponent n are used, as well as other criteria hardening derived from them, such as R_e/R_m, (R_e/R_m), A, etc. These criteria only apply to the material and to the uniaxial scheme of main stress. The pressability of sheets under particular conditions is evaluated using technological tests, such as the Erichsen cupping test. In this test, the formability criterion is the depth at which a crack is formed when a pushing a punch with a spherical end of a prescribed radius into the sheet, so-called Erichsen number IE, but also the appearance of the impressed spherical cap. The material characteristics of steel sheet in the forming process are also significantly influenced by external factors. The strain rate is a significant external factor and the intensity of its influence on the behaviour of material during the forming process, and hence on the material characteristics, is a function of its internal structure. With increasing the strain rate, the critical slip stress increases, the yield point intensively increases, the ultimate tensile strength increases and the material deformation characteristics change. As a result, the values of formability criteria derived from these characteristics also change. One of possibilities to increase the productivity during cold forming consists in increasing the forming (pressing) rate. Therefore it is necessary to know the behaviour of material in the forming process at increased rates, as well as its material characteristics. The compactness of the surface zinc layer is an important requirement for these materials, mainly at high loading rates. This information can be provided by modified dynamic Erichsen tests, or cyclic loading tests. Measuring

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of the material characteristics using the tensile test at high strain rates is very difficult and therefore possibilities to evaluate the material characteristics using modified tests are looked for [1-7].

Microalloyed steels meet increased requirements for utility properties of deep-drawing sheets. These steel sheets, as a result of their controlled forming and microalloying, have significantly higher strength and fatigue properties, while keeping good formability as traditional deep-drawing sheets. In terms of the automotive industry, corrosion resistance is also very important, and therefore these sheets are surface-treated. Surface treatment can have an effect on the pressing technology process, as well as on the utility properties.

The aim of the paper is to analyze the deep-drawing properties of light-gauge surface-treated sheets made of microalloyed steels suitable for the automotive industry, determined using various testing procedures, to point out their mechanical and fatigue properties, as well as the behaviour of their surface layer during plastic deformation and after fatigue loading, and also to assess the influence of the loading (strain) rate on material characteristics and formability.

EXPERIMENTAL WORK

The experiments were made on samples taken from steel strips produced by cold forming and then hot dip galvanized, made of H260LAD, H340LAD and H420LAD grades, intended for production of heavy-loaded pressings in the automotive industry. The target chemical composition of the tested steels is shown in Table 1.

The strip thickness ranged between 1-1,5 mm. The yield point ranged between R_e = 320 – 475 MPa. The microstructure of the tested steel sheets is polyedric, ferritic, with a small share of fine pearlitic grains precipitated at the boundaries of ferritic grains. The zinc layer thickness ranged from 8 to 14 μm.

From the steel strips H260LAD and H340LAD thick 1 mm and the steel strip H420LAD thick 1,5 mm, samples were taken in the rolling direction, then flat tensile test bars with the width of 10 mm were made, as well as strips with the width of 90 mm for the Erichsen cupping test were made. The tensile test was carried out on the tensile testing machine TiraTEST 2300 and the mechanical properties of the tested sheets were evaluated.

The Erichsen cupping test was carried out on the tested sheets according to STN 42 0406 Standard and also a modified cupping test was carried out at the strain rates from 0,2 to 150 m/min. The modified Erichsen test was carried out using a fixture, whose dimensions of the spherical punch and the die were the same as for the Erichsen test instrument, on the tensile testing machine INSTRON 1185 and on the drop tester. The biaxial tensile cupping test was carried out on the hydraulic press BZE 100 using the drawing tool with a hemispherical drawing punch (R = 74 mm). The height of the spherical cup at the moment of failure of the sheet, the crack shape after failure and the surface of the spherical cup are the measures of the plastic properties of the tested sheet.

From the tested sheets, test bars were taken for flat bending fatigue tests at the symmetric tension-compression cycle and the loading frequency of 35 Hz. The limit number of oscillations N_C=10^7 was taken as the flat bending fatigue limit σCo. The behaviour of the surface layer was observed using a scanning electron microscope.

ACHIEVED RESULTS AND THEIR ANALYSIS

The mechanical properties of microalloyed steels are a function of their microstructure, which depends on the chemical composition and the processing technology [4]. The complex mechanical properties of the investigated steels are shown in Table 2.

Table 3 shows that the tested steels have, besides very good strength properties, also sufficient plasticity. Taking into account their uniform plastic deformation (A_g), elongation (A_{80}) and strain hardening exponent (n) values, the sheets made of H260LAD and H340LAD steels can be found suitable for demanding pressings, too.

Because of the hardening mechanisms of microalloyed steels (grain refinement and precipitation), the yield point

Table 1. **Chemical composition of steel substrates, Wt. % (max.)**

Steel quality	C	Si	Mn	P	S	Al	Ti	Nb	V
H260LAD	0,01	0,10	0,9	0,080	0,025	0,02	0,10	0,022	0,10
H340LAD	0,079	0,047	0,869	0,011	0,004	0,037	0,013	0,033	0,020
H420LAD	0,077	0,013	1,224	0,020	0,005	0,041	0,014	0,053	0,033

Table 2. **Mechanical properties of tested steels**

Steel quality	$R_{p0,2}$ /MPa	R_m/MPa	A_g /%	A_{80}/%	r	n	$R_{p0,2/}$ R_m
H260LAD	320	367	21,8	35,3	1,141	0,198	0,872
H340LAD	378	439	19,5	32,2	1,054	0,186	0,861
H420LAD	475	557	11,9	19,8	0,41	0,134	0,853

Table 3. **Technological properties of tested steels**

Steel quality	I_E/mm	E /J	I_H /mm	I_{Ed} /mm	A_E /%	A_{Hstat} /%	A_{Edyn} /%
H260LAD	11,2	105	44,9	9,5	32,3	26,7	23,4
H340LAD	11,0	126	43,5	10,1	28,5	23,3	22,6
H420LAD	10,9	220	34,8	10,3	25,8	22,7	21,7

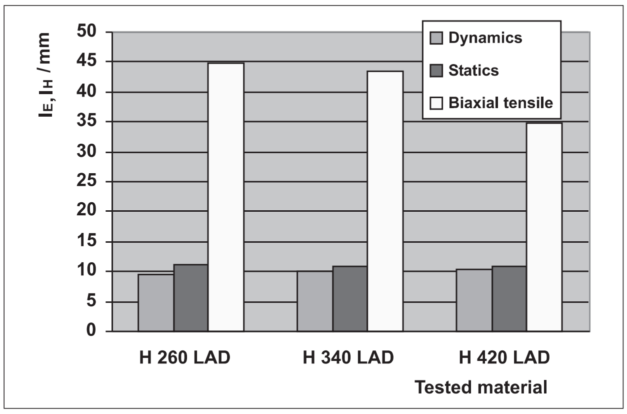


Figure 1. Erichsen number I_E by statical (v= 10 mm/min a dynamical I_{Ed} (v=2m/s) loading

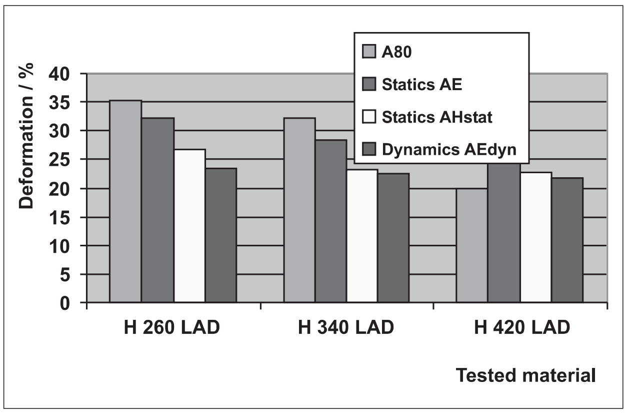


Figure 2. Comparison relatively deformation near deep-drawing test and tensibility

increases more significantly than the ultimate tensile strength, and therefore the R_e/R_m ratio is higher than in case of traditional drawing steels. However, the R_m - R_e difference is relatively high and is the guarantee of resistance of these sheets against loss of local stability during pressing, which was also confirmed by technological tests.

The technological properties of the tested steels were assessed using the Erichsen test (I_E), the modified Erichsen test at various loading rates and the cupping test (I_H), and the results are shown in Table 3.

The graph of the deep-drawing parameters for the tested materials is shown in Figures 1 – 3.

Figure 1 shows that the absolute depth of the cup at the moment of its failure is the greatest in the cupping test, which is due to a different punch diameter in the tests. It is more important to know that dynamic loading (v = 2 m/s) in the modified Erichsen test on the drop tester results in a decrease of the Erichsen number. This is also reflected in the shape of failure of the cup, as documented by Figure 4. The crack trajectory after static loading in the Erichsen test and in the cupping test corresponds to the crack trajectory for deep drawing, but this does not apply to the dynamic test (Figure 4).

For comparison of plastic properties of the tested sheets, Figure 2 shows the relative deformation of sheet at the moment of failure of the cup in the Erichsen test and the cupping test and the elongation A_{80}. Figure 2 shows that deformation after failure of the outer side of the cup in the Erichsen test is the highest and the elongation A_{80} is the lowest for the tested steels. This is influenced by the measured length of the deformed part of the sample, but also by the sheet thickness. With the increasing sheet thickness, the cup depth I_H increases, but

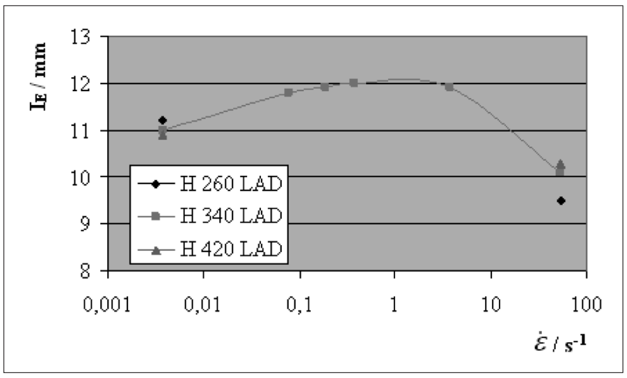
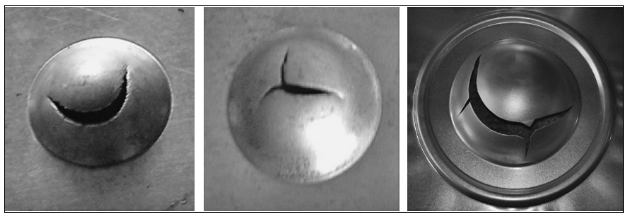


Figure 3. Influence strain rate on Erichsen number I_E



a) statics b) dynamics c) cupping test
Figure 4. Shape seed-cover after deep drawing test

the sheet thickness has no effect on A_{80}. This is also documented by the results (Figure 2), where A_{80} decreases with the increasing yield point of the tested steels, but I_H is the greatest in the deep-drawing test of H420 LAD steel. The sheet thickness of H420LAD steel is h=1,5 mm and the thickness of the other sheets is h=1 mm.

The main attention during deep-drawing tests was paid to the loading rate. Figure 3 shows the relationship between I_H and the loading rate ($\dot{\varepsilon} \approx 10^{-3}$ s^{-1}) for the tested steels. I_H during static loading is higher than during dynamic loading ($\dot{\varepsilon} \approx 10^{2}$ s^{-1}). It results from the above-mentioned that it is purposeful, especially from the practical point of view, to determine the critical strain rate at which deep-drawability decreases. Tests were carried out in the interval of the above-mentioned rates and for H340LAD steel this relationship is documented by Figure 3. Figure 3 also shows the results of measurement of I_H for H260LAD and H420LAD steels at the static rate $\dot{\varepsilon} \approx 10^{-2}$ s^{-1} and at dynamic loading - $\dot{\varepsilon} \approx 10^2$ s^{-1}. This relationship shows that with the increasing strain rate up to approx. $\dot{\varepsilon} \approx 1$ s^{-1}, deep-drawability of the tested steel increases and after exceeding this value deep-drawability decreases.

The tested sheets have also found their application in the automotive industry. On automobiles, sheets are mainly cyclically loaded (fatigue) and must resist corrosion. Therefore the fatigue properties of the tested galvanized sheets were analyzed. The results of the fatigue tests are shown in Table 4.

Table 4. **Fatigue properties tested steel H420LAD**

Steel quality	$R_{p0,2}/R_m$	σ_{Co} /MPa	σ_{Co}/R_e	σ_{Co}/R_m	a	b
H420LAD	0,853	250	0,526	0,448	8.16	-0.0093

Figure 5 documents the results of flat bending fatigue tests of the sheet made of H420LAD steel. The bending fatigue limit σ_{Co} = 250 MPa was determined for 10^7 cycles. From the inclined section of the σ - N function (which can be described by the equation $\log N = a+b.\ \sigma$), the a, b parameters were determined using linear regression.

Based on the determined results of fatigue tests, the tested sheets have very favourable fatigue properties, if we take into account their fine-grained structure.

In the fatigue tests, as well as in the tensile test and the technological tests, the integrity of the zinc coating on the tested sheets was investigated. From the macroscopic point of view, no failure of the zinc coating was observed during deformation of the samples until their failure. The analysis of fatigue fractures using a scanning electron microscope shows that the surface zinc layer is compact and was not the initiator of propagation of the fatigue crack, as documented by Figure 6.

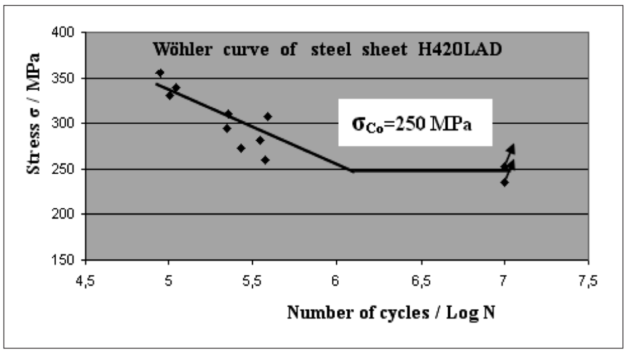


Figure 5. Wöhler curve of steel sheet H420LAD

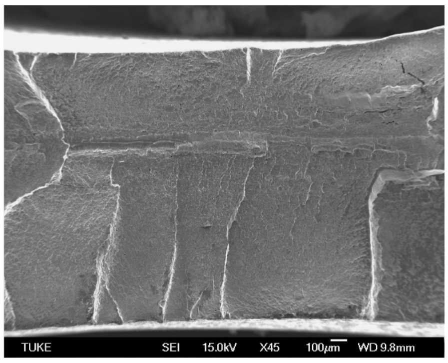


Figure 6. Fracture area near fatigue test

CONCLUSIONS

The paper analyses the mechanical, deep-drawing and fatigue properties of light-gauge galvanized sheets with the yield points of 320, 378, and 475 MPa. Based on the results of tests and their analysis, the following can be stated:

The tested steel sheets, besides high strength and fatigue properties achieved through their fine-grained structure and precipitates, have also very favourable plastic properties. These were confirmed, besides characteristics obtained in the tensile test (A_g A_{80}, n), also by the Erichsen test and the biaxial tension cupping test.

The strain rate during pressing (in the Erichsen test) influences the value of impression to failure of the cup I_H. Up to the rate of approx. 1 s^{-1}, I_H increases, and after exceeding this value it decreases. This finding enables the use of traditional deep-drawing criteria in assessing the deformation limit states.

The zinc coating was compact during deformation up to the moment of failure of the samples, without loss of cohesion with the sheet, and was not the initiator of formation and propagation of cracks.

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