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THE RATE OF STABLE CRACK GROWTH (SCG) IN AUTOMOTIVE STEELS SHEETS

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The main aim of this paper is determining the stable crack growth (SCG) rate for automotive steel sheets. The SCG was monitored using the non-contact videoextensometry technique. CT (Compact Tension) specimens of three steel grades were loaded by eccentric tension under two loading conditions. The SCG characteristics including rate depend on steel grade, on the rolling direction as well as on the loading rate. Linear relation between the SCG rate and δ_R-curve slope was determined.

Key words: steel, sheet, stable crack growth, rate, videoextensometry.

INTRODUCTION

The stable crack growth (SCG) rate is sufficiently explored for thicker sheets, but not for steel sheets (1 – 2 mm) used for the automotive body. These thin sheets must have equally high resistance toward potential crack growth initiated by crash and so guarantee the safety.

Commonly used for SCG is dependence between the applied value of *J*-integral and the amount of stable crack extension Δa (the J_R-curve), although it depends on the geometry of the specimen or the component [1]. The full J_R-curve is a material property and is indicative of the materials toughness [2]. The range of validity, i.e. the geometry independence is obviously much larger for crack tip opening displacement (*CTOD*) resistance curve, δ_R-curve [3]. The *CTOD* (δ) is an alternative to the *J*-integral for representing the crack growth resistance of materials under elastic-plastic condition. Linear relationship between *CTOD* and *J*-integral exists [4].

During the SCG testing – due to plastic deformation, caused by the crack tip blunting, the stretch zone (SZ) is generated.

In work [5] the stretch zones in thin steel sheets for the automotive body were evaluated and relation (1) between the stretch zone width w_{SZ} and height a_{SZ}, and also relation (2) between w_{SZ} and *CTOD*, were determined:

$$w_{SZ} = 0{,}171\, a_{SZ} - 0{,}0156, \qquad (1)$$

$$w_{SZ} = 0{,}0855\, CTOD - 0{,}0156. \qquad (2)$$

Direct relationship between w_{SZ} and *CTOD* exists [6], which also confirms determined linear relation (2) for thin steel sheets.

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The R-curve slope characterizes the crack growth resistance. The crack growth resistance characteristics are *T*, *dJ/da* and *dCTOD/da*. The SCG characteristic tearing modulus *T* includes the J_R-curve slope *dJ/da*. The tearing modulus is a measure of the resistance of the material to tearing and an indication of the stability of the crack growth [7]. The *dCTOD/da* represents a dimensionless form of the δ_R-curve slope.

The aim of this work was to analyse the effect of the loading rate, the material, and the rolling direction on the SCG rate.

EXPERIMENTAL

Steels

Three grades of zinc-coated automotive steel sheets were used for the investigation: (a) IF – deep drawing interstitial free steel with ferrite microstructure (C = 0,0013 %), (b) FP – microalloyed steel with ferrite-pearlite microstructure (C = 0,16 %) and (c) DP – dual phase steel with ferrite-martensite microstructure (C = 0,072 %). Mechanical properties: 0,2 % offset yield strength $R_{p0,2}$, yield strength R_e (marked in Table 1 by *), tensile strength R_m, elongation A_{80} and thickness *B* of the investigated steels are shown in Table 1 in both directions, perpendicular (T) and parallel to the rolling direction (L).

Table 1 **Mechanical properties of automotive steels**

Steel	B / mm	$R_{p0,2}$ / MPa	R_m / MPa	A_{80} / %
IF T	1,95	171	287	48,2
IF L		182	285	46,1
FP T	1,80	370*	455	27,7
FP L		350*	443	26,3
DP T	1,60	388	581	26,1
DP L		372	570	26,2

IF steels have interstitial C and N atoms untied to stable forms, and therefore do not require additional overage and may be processed at a high heating rate and movement of the band, which are necessary for galvanizing or continuous annealing.

DP steels are characterized by containing about 5 - 40 % of martensite in the ferritic matrix [8], and have: a low tendency to aging, high strength, and good plastic properties, but low yield strength. A disadvantage is the relatively low coefficient of normal anisotropy.

The microalloyed steels usually have a ferrite-pearlite structure, they are a fine grain steels in aggregate micro-alloying content is below 0,15 % [9]. From the physical-metallurgical point of view uniform fine-grained structure, good steel purity, and precise control of the level of precipitation strengthening is required.

Specimen geometry and loading

The SCG testing was performed using CT specimens (W = 50 mm) with an electro-spark-produced notch with tip radius 0,1 mm, however, CT specimen usually has notch that ends with a fatigue crack.

In [10] no important differences in the stable crack growth characteristic dCTOD/da of both fatigue pre-cracked and electro-spark notched specimens of investigated steels were determined.

Since CT specimens of thin sheets are prone to buckling [11], specimens with anti-buckling plates [12] were loaded (0,0217 and 2,17 mm·s^{-1}) by eccentric tension on a tensile testing machine FP 100/1, whereby the deformation in the notch area was recorded by a non-contact displacement measurement – a videoextensometry technique [13].

RESULTS AND DISCUSSION
Crack growth rate

The SCG rate of the automotive steel sheets was studied under two loading conditions; Figure 1 shows typical plots for crack growth kinetics. During the period of crack growth, on vertical part of curve in Figure 1, the SCG rate *da/dt* for each investigated material was determined.

The SCG rate (Table 2) of steel FP reaches the highest values, the lowest values were determined for steel IF. The SCG rate of investigated steels depends on the orientation of the crack to the rolling direction as well as on the loading rate. The SCG rate of investigated steels increases with decreasing SCG resistance.

The SCG rate, when the crack growth is in the rolling direction (TL), is higher than in the case of crack growth in the direction perpendicular to the rolling direction (LT). The failure in different planes affects inclusions in different ways [14]. Inclusions (sulphides) direct by rolling in rolling direction and this result to band microstructure, which was supported on steels DP and FP by SEM and causes a SCG rate deceleration.

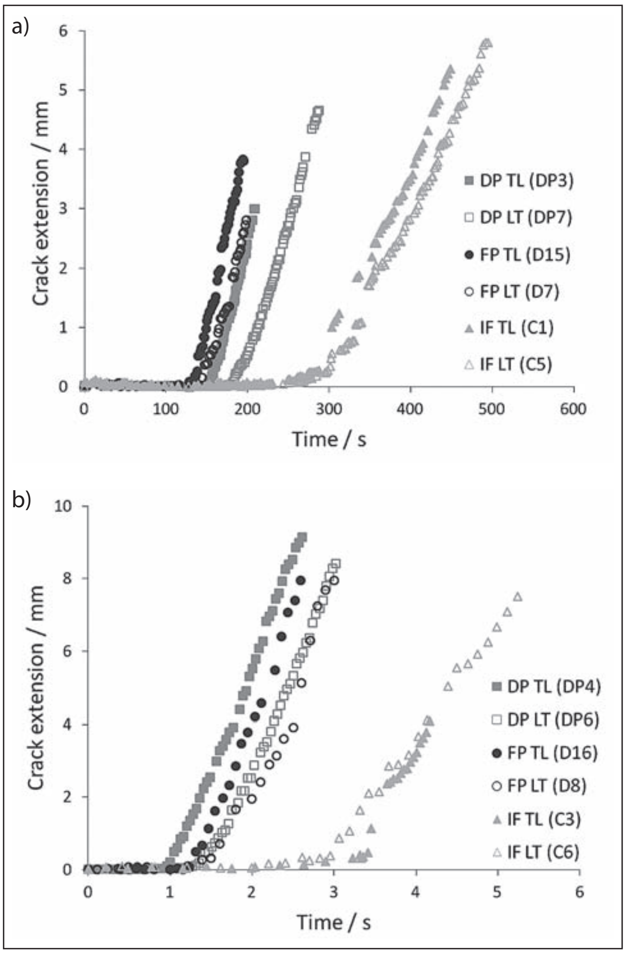

Figure 1 SCG rate of automotive steels, (a) loading rate 0,0217 mm·s^{-1}, (b) loading rate 2,17 mm·s^{-1}

Influence of loading rate on the SCG rate is not negligible. By the loading rate of 2,17 mm·s^{-1} SCG rates of investigated steels reach 100 times higher values as by loading rate of 0,0217 mm·s^{-1}.

Stable crack growth characteristics

R-curves of investigated steels were determined in terms of both J-integral and *CTOD* values by loading rates (0,0217 and 2,17 mm·s^{-1}). Maximum J-integral as well as *CTOD* were obtained for IF steel.

The *dCTOD/da*, *dJ/da*, and T modulus reach the maximum values for IF steel. Minimum values were determined for FP steel. The IF steel has the highest crack growth resistance [10]. T modulus, slope *dJ/da* and *dCTOD/da* of investigated steels (Table 2) increase with increasing ductility, SCG resistance characteristics of higher strength steels (FP and DP) increase with both yield stress and tensile strength increasing.

Crack growth direction significantly affects the SCG resistance. The most sensitive steel in the crack growth direction is DP steel. The crack growth resistance is higher for crack growth perpendicular to the rolling direction by 1,8 – 23,3 % in dependence on steel grade and loading rate.

Loading rate affects the crack growth resistance. The crack growth resistance characteristics of investi-

Table 2 **SCG characteristics of automotive steels for both loading rates**

	0,0217 $mm \cdot s^{-1}$				2,17 $mm \cdot s^{-1}$			
Steel	da/dt	dJ/da	T	dCTOD/	da/dt	dJ/da	T	dCTOD/
	/ $mm \cdot s^{-1}$	/ $N \cdot mm^{-2}$	/ -	*da* / -	/ $mm \cdot s^{-1}$	/ $N \cdot mm^{-2}$	/ -	*da* / -
IF TL	0,0296	145	528	0,551	3,527	152	550	0,481
IF LT	0,0284	148	538	0,577	3,0722	154	560	0,593
FP TL	0,0648	91,3	100	0,231	6,0731	98,4	108	0,324
FP LT	0,0563	94,6	104	0,239	5,5066	114	125	0,345
DP TL	0,0575	130	124	0,288	5,9035	134	129	0,297
DP LT	0,0499	140	134	0,336	5,3904	143	137	0,353

gated steel by loading rate 2,17 $mm \cdot s^{-1}$ are larger by 2,4 – 44,4 % in dependence of the steel grade and the crack growth direction. The steel most sensitive to the loading rate is FP steel.

Creation of regression models

The SCG of automotive steel sheets is assessed using the basic mathematical and statistical methods. Estimates of coefficients of the researched regression models are made using the regression analysis. Values shown in Table 2 were used to produce several relations with a better predictive ability with regard to results. The relations for both loading rates between the slope *dCTOD/da* and the SCG rate *da/dt* can be described by the models with point estimates listed in Table 3. Monitored relations can be described by a linear regression model.

Table 3 **Regression models**

Loading rate / $mm \cdot s^{-1}$	Regression model	R^2
0,0217	$dCTOD / da = 0{,}847 – 9{,}983 da / dt$	0,970
2,17	$dCTOD / da = 0{,}825 – 0{,}087 da / dt$	0,945

CONCLUSION

Based on obtained results it can be concluded that the SCG resistance of thin steel sheets can be predicted by SCG rate. There exists direct relationship between the slope *dCTOD/da* and the SCG rate *da/dt*, and by using it we can easily determine δ_R –curve slope, i.e. without having to establish the *CTOD*.

The SCG rate of investigated steels increases with SCG resistance decreasing. The SCG rate of steel FP is the highest, whereas lowest values were determined for steel IF, which has the highest crack growth resistance. The SCG rate of the investigated steels depends on the orientation of the crack with respect to the rolling direction as well as to the loading rate. The SCG runs faster for crack growth in the rolling direction in comparison with the crack growth in the direction perpendicular to the rolling direction. At the loading rate of 2,17 $mm \cdot s^{-1}$ the SCG rate of investigated steels reach 100 times higher values than at loading rate of 0,0217 $mm \cdot s^{-1}$.

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Note: The English Language translation was done by Ladislav Pivka, Košice, Slovakia