The crack growth resistance of thin steel sheets under eccentric tension

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Abstract. The stable crack growth in thin steel sheets is the topic of this paper. The crack opening was observed using a videoextensometry system, allowing the crack extension determination. J_R -curve and δ_R -curve were established from obtained data. The ductile tearing properties of different thin sheets of steel were determined, including the impact of the specimen orientation, from test performed on compact tension specimens loaded under two conditions. The effect of the material, the rolling direction, and loading rate on the crack growth resistance of thin steel sheets was analyzed. In addition to the crack growth resistance, J -integral values for crack initiation were also estimated. The relation between J_i and $J_{0.2}$ was assessed using the basic mathematical and statistical methods. This relation was described by a linear regression model.

Keywords. Cold-formed steel; thin sheet; stable crack growth; R-curve; videoextensometry.

1. Introduction

Evaluation of the stable crack growth is reworked enough 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. The eccentric tension is commonly used for the stable crack growth testing. The load passes by eccentric tension at a certain distance from the crack root. The bending torque creates and it causes a maximum tensile load at the root [1]. The crack growth resistance curve (R-curve) is a suitable method to evaluate the initial stage of stable crack growth [2]. It characterizes the crack growth resistance of a ductile material. Used types of R-curves are:

- J_R -curve (dependency of J on Δa), where J is the value of the J -integral corresponding to the stable crack extension Δa [3], J -integral represents the external load and characterizes the stress state in the vicinity of the crack root, Δa is the displacement of the crack due to external load,
- δ_R -curve (dependency of $CTOD$ on Δa), where $CTOD$ is a crack tip opening displacement corresponding to the stable crack extension Δa [4].

The J_R -curve is indicative of the materials toughness. As with J , several $CTOD$ parameters are defined to describe

the various stages and events during ductile and brittle fracture [5].

The stretch zone (SZ) formation prevents the stable crack growth and it is caused by the crack tip blunting. The stretch zone size can be correlated with $CTOD$, so the stretch zone dimensions can be its measure [6]. The relationship between the critical $CTOD$ for ductile crack initiation δ_i and the stretch zone width w_{SZ} [7] takes the general form of

$$\delta_i = \delta_0 + \alpha \cdot w_{SZ}, \quad (1)$$

where δ_0 is the $CTOD$ at which stretch zones appear on fracture surfaces and is usually considered to be zero. The α is a parameter that depends on the geometry of the blunted crack tip, the definition of $CTOD$ and the method for w_{SZ} measurement. The experimental obtained values of α vary from 1 to 20 [7]. The stretch zones of thin steel sheets were established in work [8]. Between w_{SZ} and the stretch zone height a_{SZ} and also between w_{SZ} and $CTOD$ were determined relation:

$$w_{SZ} = 0.171a_{SZ} - 0.0156, \quad (2)$$

$$w_{SZ} = 0.0855CTOD - 0.0156. \quad (3)$$

Direct relationship exists between the w_{SZ} and $CTOD$ [9], which also confirms determined linear relation (3) for thin steel sheets. The δ_0 is usually considered to be zero and so (3) will change:

$$w_{SZ} = 0.0785CTOD. \quad (4)$$

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This new determined relation (4) can be transcribed:

$$CTOD = 12.7w_{SZ} \quad (5)$$

and for automotive thin steel sheets the value of the parameter α is 12.7.

In this work the crack growth resistance of three grades of zinc-coated automotive steel sheets (IF – deep drawing interstitial free steel, DP – dual-phase steel, and microalloyed steel) was determined.

The IF steels are used for the production of extra deep drawing hot dip galvanized sheets for demanding automotive stampings [10]. With respect to the desired properties it is necessary to the greatest extent possible, to attach the already low concentrations of dissolved interstitial compounds to stable compounds of carbide formers and nitride formers [11]. The IF steels have interstitial C and N atoms untied to stable forms, and therefore not require additional aging and may be processed at a high heating rate and movement of the band, which are necessary for galvanizing or continuous annealing [10]. These steels were developed to achieve extremely high levels of deep drawing. This property is preferred at the expense of strength values, which normally degrades the ability of deep drawing [12].

DP steels are characterized by containing about 5–30% of martensite in the ferritic matrix [13], and have a low tendency to aging, high strength, and good plastic properties, but low yield strength [11]. Initially, DP steels were developed for the needs of the automotive industry, due to their increased plastic properties like low alloy steels of equivalent strength [14]. A disadvantage is the relatively low coefficient of normal anisotropy [15]. In terms of technological production, low carbon dual-phase steels with ferrite–martensite microstructure are obtained by controlled rolling and cooling or intercritical annealing [16]. DP steels are required in particular by producers of car wheels [17]. Their use is still expanding because of their high strain hardening exponent and more uniform deformation. They are used for production buffers, the chassis components, and so on [18].

The microalloyed steels usually have a ferrite–pearlite structure, and they are a fine grain steels with small quantities of one element or combinations of elements of Al (min. 0.015%), Ti (max. 0.1%), Nb (max. 0.04%) and V (max. 0.15%), in aggregate micro-alloying content is below 0.15% [19]. They are used for dynamic stressed parts requiring excellent strength and fatigue characteristics while keeping an excellent bendability and draw ability at mild to moderate degrees of drawing. 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. The advantage of these steels is that in addition to maintaining good deep drawing level they have low coefficients of normal anisotropy and are suitable for difficult shape moldings with great resistance to indentation [15].

This work aimed to analyze the effect of the material, the rolling direction, and loading rate on the crack growth resistance of thin steel sheets.

2. Material and methods

Three grades of zinc-coated thin steel sheets (figure 1) were used for the investigations:

- deep drawing interstitial free steel XSG with ferrite microstructure ($C = 0.0013\%$),
- microalloyed steel HR 45 with ferrite–pearlite microstructure ($C = 0.16\%$),
- dual-phase (DP) steel with ferrite–martensite microstructure ($C = 0.072\%$).

Thickness B and mechanical properties by loading rate 0.0217 mm/s (0.2% offset yield strength $R_{p0.2}$, yield strength R_e , tensile strength R_m , and elongation A_{80}) of the investigated steel sheets are shown in table 1.

The stable crack growth testing was performed using compact tension (CT) specimens ($W = 50$ mm) with an electro-spark produced notch with tip radius 0.1 mm, but CT specimen usually has notch that ends with a fatigue precrack. No important differences in the stable crack

Figure 1. Microstructure of the investigated steels: (a) XSG, (b) HR 45, and (c) DP.

Table 1. Mechanical properties of the investigated steels.

Steel	<i>B</i> (mm)	Direction	$R_{p0.2}$ (MPa)	R_m (MPa)	A_{80} (%)
XSG	1.95	T	171	287	48.2
		L	182	285	46.1
HR 45	1.80	T	370 ^a	455	27.7
		L	350 ^a	443	26.3
DP	1.60	T	388	581	26.1
		L	372	570	26.2

^a R_e – upper yield strength, yield strength for 0.2% deformation ($R_{p0.2}$) is determined in case of missing R_e .

L, loading in parallel direction to rolling direction; T, loading in perpendicular direction to the rolling direction.

growth resistance of both fatigue precracked and electro-spark notched specimens of investigated steels were observed in [20].

Since CT specimens of thin sheets are prone to buckling [21–24], specimens with anti-buckling plates (figure 2) were loaded (0.0217 and 2.17 mm/s) by eccentric tension on a tensile testing machine Heckert Vebthüringer Industriewerk Rauenstein type FP 100/1 (loads up to 100 kN), whereby the deformation in the notch area was recorded by a non-contact displacement measurement – a videoextensometry technique [25, 26].

The crack mouth opening displacement (CMOD) was determined by continual recording of the co-ordinates of centre of gravity of the dots applied properly in the notch area by appropriate software. The crack growth Δa was evaluated using a special program based on MATLAB software from recorded images in both directions, perpendicular (LT) and parallel to the rolling direction (TL). The *CMOD* values have been transformed to *CTOD* [27] values using the plastic hinge model [28]:

$$CTOD = \frac{[n(W - a) + \Delta a]V}{[n(W - a) + a + z]} \quad (6)$$

Figure 2. CT specimen with anti-buckling plates.

where n , W , a , Δa , V , and z denote $n = 0.4(1 + \beta)$; $\beta = f(\frac{a}{W-a})$, width of specimen, crack length, crack growth, notch opening and distance of measurement point from the load-line (if displacement is measured along the load-line, $z = 0$), respectively.

The *J*-integral values were determined accordingly [28]:

$$J = \frac{\eta A}{B(W - a_0)} \quad (7)$$

where $\eta = 2 + 0.522(1 - a_0/W)$, A is the area under the load–displacement curve, B is thickness of specimen, and a_0 is the initial crack length.

R-curves were determined from the obtained data. R-curve characterizes the crack growth resistance of a ductile material. The relationship between the applied value of *J*-integral and amount of the stable crack extension (Δa) is known as the J_R -curve. The *J*-integral and J_R -curve are the most important material parameters in elastic–plastic fracture mechanics [29]. The crack tip opening displacement *CTOD* (δ) is an alternative to the *J*-integral for representing the crack growth resistance of materials under

Figure 3. J_R -curve of the investigated steels: (a) loading rate 0.0217 mm/s and (b) loading rate 2.17 mm/s.

Figure 4. δ_R -curve of the investigated steels: (a) loading rate 0.0217 mm/s and (b) loading rate 2.17 mm/s.

Table 2. The crack growth resistance characteristics of the investigated steels.

Steel	0.0217 mm/s			2.17 mm/s		
	dJ/da (N/mm ²)	T (–)	$dCTOD/da$ (–)	dJ/da (N/mm ²)	T (–)	$dCTOD/da$ (–)
XSG TL	145	528	0.551	152	550	0.481
XSG LT	148	538	0.577	154	560	0.593
HR 45 TL	91.3	100	0.231	98.4	108	0.324
HR 45 LT	94.6	104	0.239	114	125	0.345
DP TL	130	124	0.288	134	129	0.297
DP LT	140	134	0.336	143	137	0.353

LT, crack growth in perpendicular direction to the rolling direction; TL, crack growth in parallel direction to the rolling direction

elastic–plastic condition. $CTOD$ resistance curve, δ_R -curve, was established for each steel too.

The tearing modulus T is a measure of the resistance of the material to tearing and an indication of the stability of the crack growth. The tearing modulus represents a dimensionless form of the J_R -curve slope and is expressed by the following equation [30, 31]:

$$T = \frac{dJ}{da} \frac{E}{R_{em}^2}; R_{em} = \frac{R_e + R_m}{2} \quad (8)$$

where dJ/da is the J_R -curve slope, E is Young's modulus, R_e is yield strength, and R_m is tensile strength.

3. Results and discussion

Monitoring the crack growth by a camera is not uncommon [32, 33] and crack growth tests are mostly based on the periodical extraction of crack length information [34]. Determined R-curves are presented in figures 3 and 4 in terms of both J -integral and $CTOD$ under two loading

conditions. Between $CTOD$ and J -integral exists a linear relationship [35]. The full J_R -curve is a material property [5]. The J_R -curve for the stable crack growth is commonly used, although it is accepted that the J_R -curve may depend on the geometry of the specimen or of the component [36]. The range of validity (i.e., the geometry independence) is obviously much larger for δ_R -curve than that for J_R -curve [37].

Maximum $CTOD$ as well as J -integral values were obtained for XSG steel, whereby comparing the loading rates higher values of J -integral and $CTOD$ were determined by the loading rate of 2.17 mm/s.

The R-curve slope characterizes the crack growth resistance and is shown in table 2. The crack growth resistance characteristics ($dCTOD/da$, dJ/da and T) of steel XSG (table 2) reach the highest values, lowest values were determined for steel HR 45. The crack growth resistance characteristics of the investigated steels depend on the orientation of the crack to the rolling direction as well as on the loading rate.

The crack growth resistance characteristics were analysed in dependence of tensile properties (yield stress $R_{p0.2}$ or R_e , tensile strength R_m and elongation A_{80}). Dependency of both T and $dCTOD/da$ on mechanical properties is shown in figure 5. The dependence for dJ/da is identical as for T .

We found that T and $dCTOD/da$ of investigated steels increase with increasing ductility.

T and $dCTOD/da$ of higher strength steels (HR 45 and DP) increase with increasing both yield stress and tensile strength. XSG steel with lowest both yield stress and tensile strength has 2–3× higher values of T and $dCTOD/da$ comparing with DP and HR 45.

The crack growth resistance characteristics by the crack growth in the direction perpendicular to the rolling direction (LT) are higher as compared to that in the rolling direction (TL) (table 2). The inclusions are responsible for initiating and developing of failure, and they affect failure

Figure 5. Relation between both, T , $dCTOD/da$ and tensile properties.

Figure 6. The crack growth resistance characteristics of the investigated steels: (a) loading rate 0.0217 mm/s and (b) loading rate 2.17 mm/s.

in different planes differently [38]. Inclusions (sulphides) direct by rolling in rolling direction and this result in band microstructure, which was supported on steels DP and HR 45 by SEM.

The crack growth resistance characteristics (T and $dCTOD/da$) of the investigated steels for various loading rates are presented in figure 6.

The crack growth resistance characteristics of steel HR 45 by loading rate 0.0217 mm/s in direction perpendicular to the rolling direction (LT) are slightly higher than in the rolling direction (TL). Differences of individual characteristics for other steels are diverse. Slope $dCTOD/da$ of XSG steel for LT direction is higher by 23% comparing with the TL direction by loading rate 2.17 mm/s, this is the

maximum difference found. Slope dJ/da and T of XSG steel investigated loading rates for LT direction are slightly higher than for TL direction. Slope $dCTOD/da$ of XSG and DP steels for LT direction reaches maximum difference comparing with TL direction for both loading rates.

Influence of loading rate on the crack growth resistance is not negligible. By the loading rate of 2.17 mm/s characteristics $dCTOD/da$, dJ/da and T of investigated steels reach higher values as by loading rate of 0.0217 mm/s except the slope $dCTOD/da$ of XSG steel for TL direction. Slope dJ/da and T of steels reach the same differences by comparing both loading rates. The crack growth resistance characteristics of steel DP for TL direction by loading rate 2.17 mm/s are slightly higher than by loading rate 0.0217 mm/s. The differences for individual characteristics

Figure 7. Method of determining $J_{0.2}$ values.

Figure 8. Relation between J_i and $J_{0.2}$.

of investigated steels are diverse in other cases. Slope $dCTOD/da$ of steel HR 45 is larger by the loading rate of 2.17 mm/s for both directions. Characteristics of HR 45 steel for LT direction by loading rate 2.17 mm/s reach maximum differences by comparing with the loading rate 0.0217 mm/s.

In addition to the crack growth resistance characteristics were determined J -integral values for crack initiation – $J_{0.2}$ and J_i . The $J_{0.2}$, conventional crack initiation for 0.2 mm crack propagation [38], was also obtained (figure 7). The real state of crack initiation by experiments was impossible to determine; therefore, the J_i was determined for observable crack initiation at recorded images. $J_{0.2}$ for investigated steels reaches higher values than J_i , because the crack extension for J_i is below the 0.2 mm. It was determined a relation between $J_{0.2}$ and J_i (figure 8). Both $J_{0.2}$ and J_i for applied loadings rates are higher in case of the crack growth in direction perpendicular to the rolling direction (LT) as by the crack growth in the rolling direction (TL) with an

exception of XSG steel by rate 0.0217 mm/s. Maximum $J_{0.2}$ as well as J_i values were determined for XSG steel and minimum for DP steel.

The relation between J_i and $J_{0.2}$ is assessed using the basic mathematical and statistical methods. Estimation of coefficients of the researched regression model is made using the regression analysis. This relation can be described by a linear regression model ($R^2 = 0.949$):

$$J_i = 1.032J_{0.2} - 119.39. \quad (9)$$

4. Conclusions

As with J_R -curve, δ_R -curve can describe the various stages and events during the stable crack growth. The crack growth resistance characteristics (both R-curve slopes – $dCTOD/da$, dJ/da , and tearing modulus T) reach the maximum values for XSG (IF) steel. Minimum values were determined for HR 45 (ferrite–pearlite) steel. The XSG steel has the highest crack growth resistance. Maximum differences between investigated steels were determined in tearing modulus expression.

Tearing modulus and both R-curve slopes of investigated steels increase with increasing ductility. Crack growth resistance characteristics of higher strength steels (HR 45 and DP) increase with increasing both yield stress and tensile strength.

Crack growth direction significantly affects the crack growth resistance. The most sensitive steel on 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 of steel grade and loading rate.

Loading rate affects the crack growth resistance. The crack growth resistance characteristics of investigated steel by loading rate 2.17 mm/s are larger by 2.4–44.4% in dependence of the steel grade and the crack growth direction. The most sensitive steel on the loading rate is HR 45 steel.

List of symbols

A	area under the load–displacement curve
A_{80}	elongation (initial length 80 mm)
a	crack length
a_0	initial crack length
a_{SZ}	stretch zone height
Δa	crack propagation
α	parameter, values vary from 1 to 20
B	thickness
$CMOD$	crack mouth opening displacement
CT	compact tension
$CTOD$	crack tip opening displacement
(δ)	

δ_0	CTOD at which stretch zones appear on fracture surfaces
δ_i	critical CTOD for ductile crack initiation
δ_R -curve	CTOD resistance curve
$dCTOD/da$	slope of δ_R -curve
DP	dual-phase steel
dJ/da	slope of J_R -curve
E	Young's modulus
HR 45	microalloyed steel
IF	interstitial free steel
J -integral	line integral (path-independent) around the crack tip
J_i	value of J -integral for observable crack initiation
J_R -curve	J -integral resistance curve
$J_{0.2}$	value of J -integral of conventional crack initiation for 0.2 mm crack propagation
R_e	yield strength
R_m	tensile strength
$R_{p0.2}$	0.2% offset yield strength
SEM	scanning electron microscopy
SZ	stretch zone
T	tearing modulus
V	notch opening
W	width
w_{SZ}	stretch zone width
z	distance of measurement point from the load-line

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