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FRACTURE SURFACE DIGITIZING OF SPECIMEN FROM DROP-WEIGHT TEAR TEST

DIGITALIZACE LOMOVÉ PLOCHY TĚLESA ZE ZKOUŠKY PADAJÍCÍM ZÁVAŽÍM

Abstract

There is always a need to determine a fraction of the ductile, and respectively, brittle fracture on the fracture surface of specimen examined using a drop-weight tear test (DWTT). Determination of the percentage of ductile fracture (PDF) in accordance with valid national and international recommendations is not entirely unambiguous. Results of evaluation show a large scattering for each criterion, and depend on the subjective view of the evaluator. Criteria are complex in nature and are independent of the fracture morphology. The dimensionless areas ratio criterion has been newly proposed for the evaluation of the DWTT specimens. This criterion is given by the ratio of the fracture surface projection into a base plane to the scanned fracture surface. The fracture surface of the DWTT specimen is scanned using a 3D-Cam scanner into a network of discrete points. A fracture surface area is calculated from the sum of the areas of triangles constructed above the element of the projection of fracture surface. A dimensionless areas ratio criterion is sensitive to a change of the size of fracture surface evaluated and its value depends on the proportion of PDF in the specimen. An application of the proposed assessment of fracture surfaces in the DWTT specimens in engineering practice will contribute to the objectivity of DWTT test results and to improve equipment reliability, in which the DWTT test result is a part of attestations in materials used.

Abstrakt

Na lomové ploše tělesa zkoušky padajícím závažím (DWTT) je nutné vždy stanovit podíl houževnatého, resp. křehkého lomu. Určení procenta houževnatého lomu podle stávajících národních a mezinárodních norem není zcela jednoznačné. Výsledky hodnocení vykazují u jednotlivých kritérií velký rozptyl a jsou závislé na subjektivním pohledu hodnotitele. Kriteria mají komplexní charakter a nezávisí na charakteru lomu. Nově je pro hodnocení DWTT těles navrženo bezrozměrné kritérium poměru ploch. Toto kritérium je dáno poměrem průmětu lomové plochy do roviny podstavy vzhledem k naskenované lomové ploše. Lomová plocha DWTT tělesa je naskenována pomocí skeneru 3D-Cam do sítě diskrétních bodů. Plocha povrchu lomu je spočítána ze součtu ploch trojúhelníků sestrojených nad elementem průmětu lomové plochy. Bezrozměrné kritérium poměru ploch je citlivé na změnu velikosti vyhodnocované lomové plochy a jeho hodnota je závislá na podílu PDF v tělese. Uplatnění navrženého vyhodnocení lomových ploch DWTT těles v technické praxi přispěje k objektivizaci výsledků DWTT zkoušky a ke zvýšení spolehlivosti zařízení, u kterých je výsledek DWTT zkoušky součástí atestů používaných materiálů.

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1 INTRODUCTION

The drop-weight tear test (DWTT) has been widely used as a standard method for evaluating the resistance to fracture propagation in pipelines [1, 2] used for gas and/or oil transportation. In general, the pipelines are even used in places with the temperatures close to -40 °C, and in such an environment it is necessary to guarantee the resistance of the materials used for a pipeline production against the initiation of the unstable fracture. The evaluation of the resistance of these materials is performed by the DWTT test.

For the DWTT test it applies that the thickness of the test specimen is identical to the thickness of steel sheet metal for pressure vessels or pipelines. The abnormal fracture appearance [2] occurring when cleavage fracture follows immediately after the initiation of shear fracture at the notch can be observed in the DWTT specimens. The appearance of abnormal fracture causes difficulties in a proper assessment of the PDF, which is the main parameter monitored, thus the development of objective methods is needed.

Preparation of test specimens for the DWTT test, its procedure and method of its evaluation are standardized [3-5]. The test specimen is provided with U, V, or the Chevron notch before the test itself. During the test the specimen is placed into two supports on the side of the notch and loaded by the hammer impact of a drop tester on the opposite side of the notch. When the specimen is fractured using a single impact of the hammer the PDF can be determined on its fracture surface.

To evaluate the PDF on the fracture surface of fractured test specimens the simple relations specified in the recommendations [3, 4] can be used providing the fracture surface meets the prescribed conditions. The occurrence of abnormal fracture that is in particular common in high performance pipeline steel sheets is limiting the use of these methods to be able to accurately determine the PDF.

The need of industry practice to implement evaluations on all types of fracture surfaces of the DWTT specimens sparked the idea to develop a new method which would establish the PDF to the fracture surface, providing the correct, objective and reproducible results needed to ensure reliability and safety of pipeline systems.

The PDF of the fracture surface influences the fracture surface appearance. In general, fractures with a smaller proportion of PDF of the fracture surface are less segmented and normal lines of elements on such a surface are probably mildly deflected from the vertical line than on the fracture surface with a higher proportion of PDF. Uneven surface is assessed using/through the roughness parameter in the technical practice. The basic characteristics describing the roughness of the surface according to the recommendation [6] are the following: the mean arithmetic deviation of the profile, the height of the profile roughness determined in 10 points, the maximum height of the profile roughness, the mean span of the profile´s local projections, and the carrier proportion of the profile. Based on the predominant direction of the roughness is evaluated either in a longitudinal or transverse direction. These characteristics are determined from the actual profiles which are obtained as vertical or slant cuts in relation to the actual surface. Evaluation of the surface using this method uses only two-dimensional point information about the characteristics of the surface. However, to capture three-dimensional geometric characteristics in evaluating the surface roughness the elementary area needs to be used. To capture the complex characteristic of the fracture surface the dimensionless area ratio criterion is proposed. This test uses a three-dimensional fracture surface, and so uses a surface method of evaluation.

The paper is focused on creating a digitized model of fracture surface which is necessary to apply the proposed criteria for the PDF evaluation. The fracture surface is transferred to a network of discrete points using a 3D-Cam scanner. This network of points is modified and consequently the size of surface fracture is calculated from elementary triangular facets. The fracture surface of the set of 18 specimens of steel X70 is digitized using a proposed procedure, and the dimensionless areas ratio criterion of each specimen is calculated.

2 FRACTURE SURFACE DIGITIZING OF DWTT SPECIMEN

The fracture surface of DWTT specimen (Fig. 1) consists of the proportion of both ductile and brittle fracture. The accurate, clear and efficient determination of the PDF to the fracture surface starts from its segmentation, which can be evaluated using the surface characteristics such as roughness, inclination, and/or the size of the local surface. To determine these parameters the fracture surface must be converted into a digital form. For that purpose the fracture surface of the DWTT specimen is scanned using 3D-Cam from the Limess Company (Fig. 2).

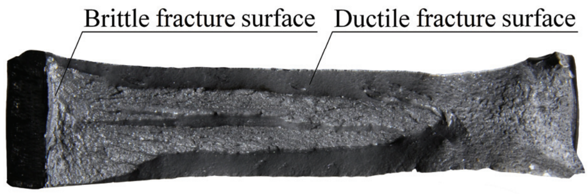

Fig. 1 Fracture surface of the DWTT specimen

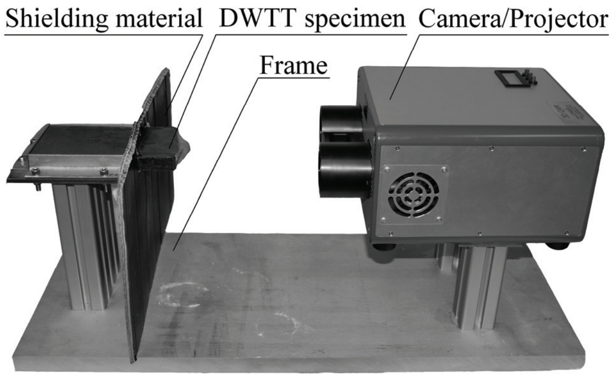

Fig. 2 Configuration for scanning of fracture surface using a 3D-Cam

The 3D-Cam is based on a triangulation technique and this consists of a camera and a fringe projector. Fringe projection is related to optical triangulation using a single point of light and light sectioning where a single line is projected onto a scanned object and viewed in a different direction. These fringes are distorted by scanning the object shape. The image analysis based on the recorded dates with the camera calculates a x, y and z coordinate of the object's surface for every image pixel.

The accuracy of the 3D-Cam strongly depends on the system calibration. The achievable resolution accuracy of the 3D-Cam depends on the distance to the object or rather on the size of the measurement field. In reference [7] of the 3D-Cam is noted that the typical measurement estimation accuracy is a 1/10000 of the image's diagonal (10 μm at 100 mm area). Major limitation of usage of the 3D-Cam [8] is caused by the measurement of the fracture surface with deep extending of the inner holes as it is displayed on the Fig. 3.

When scanning, the 3D-Cam and the DWTT specimen are fixed in to the device (Fig. 2) to maintain the same distance of the camera from the scanned specimen, as well as their alignment. Suppression of the remote background behind the scanned surface is achieved using a shadowing of background behind the specimen. To compare the contrast between lighter and darker regions of fracture surfaces it is more suitable to scan in a darker environment. Before you start scanning, the size of the aperture and time to achieve a good exposure of the fracture surface needs to be set on the 3D-Cam. The scanned fracture surface is represented by a network of three-dimensional discrete points. This network is created from the points with a non-equidistant step along the length and thickness of the fracture surface, and in addition to this it even includes the points placed in the background of the fracture surface (Fig. 4a). Coordinates of points of the scanned fracture surface are stored in a text file that is loaded into the programme designed for the PDF determination on the fracture surface of the DWTT specimen.

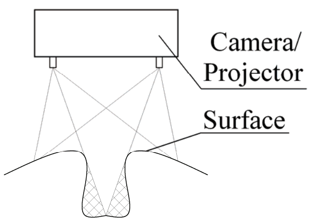

Fig. 3 Shadowing of the scanned fracture surface

Before using the designed method for determining the PDF, the scanned data is adjusted by means of our own designed software. First of all, the scanned points lying in the background of the fracture surface and points in its edges must be removed (Fig. 4a), the points in the surface holes must be extrapolated, and the heights of the fracture surface (Fig. 4b) for an equidistant step at the length and thickness of the DWTT specimen need to be approximated.

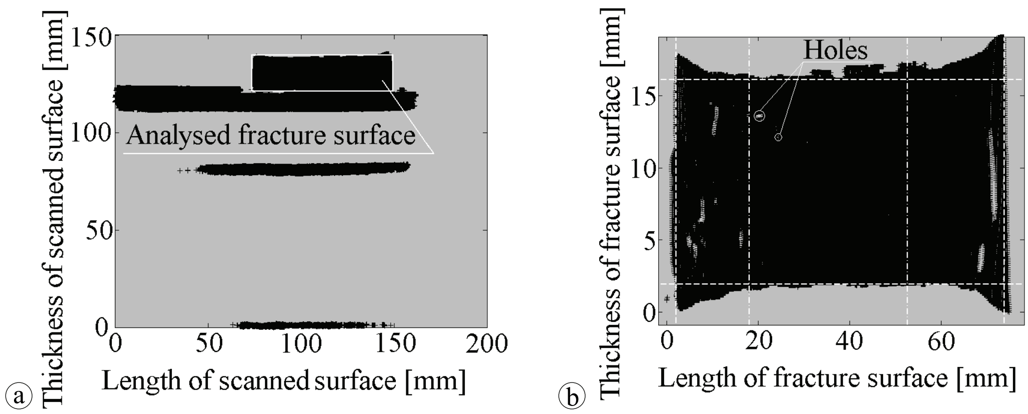

Fig. 4 Modified RAW picture from 3D-Cam (a) with background and (b) without background

The points on the edge of the fracture surface are aligned in agreement with the point with the minimum coordinate. Fig. 4b shows a trimmed fracture surface defined by a dashed line. The fracture surface for the PDF evaluation is further reduced to the area defined by two vertical dot-and-dashed lines. The reason is that the PDF is assessed for the fracture surface neglecting the region "one thickness" in length from the opposite side of the notch and "one thickness" in length from the notch root, according to the recommendations [3-5].

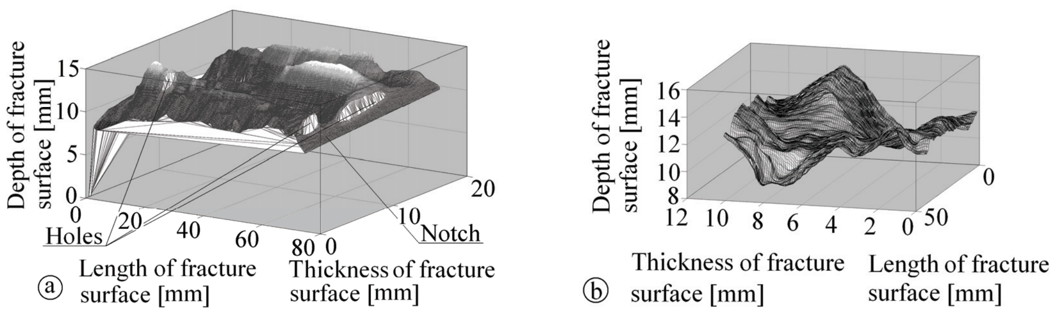

Fig. 5 (a) Unmodified fracture surface and (b) modified fracture surface

Uneven distribution of points on the fracture surface (Fig. 5a) is replaced by the network with an equidistant step (Fig. 5b). The corresponding heights of the fracture surface for the equidistant step are calculated using linear interpolation. The areas of the fracture surface which could not be converted into a digital form, and which usually lie within the edge of the fracture surface, and their size is less than 3 % of the projection size of the fracture surface (Fig. 4b) are extrapolated from the surrounding edges of the scanned fracture surface.

3 PDF CALCULATION FROM DIMENSIONLESS AREAS RATIO CRITERION

In the mentioned recommendations [3, 4] several following methods for the PDF evaluation of broken DWTT specimens are suggested: (i) measuring the PDF of the fracture surface by planimeter in a photograph, (ii) visual comparison of the fracture surface with calibrated reference specimens or their photographic images for an equal thickness of a specimen with the PDF previously specified, (iii) use of simple equations to calculate the PDF depending on characteristics of the fracture surface, and (iv) use of the chart diagram designed upon the specific configuration of the fracture surface to determine the PDF. These methods depend heavily on the subjective view of the evaluator, are poorly reproducible and are not suitable for all types of fractures.

The fracture surface with a larger PDF is usually less segmented than that of with a lower PDF. The surface is normally characterized by the arithmetic deviation of the profile, the maximum height of roughness of the profile, the mean span of roughness of the profile and by other characteristics [6]. However, these characteristics are not sufficient to fully describe the fracture surface. Additional information is provided with a proposed dimensionless areas ratio criterion. This criterion is calculated as the areas ratio, p_S, of the fracture surface projection into a base plane to the scanned fracture surface (Fig. 6a)

$$p_S = \frac{S_0}{S}, \; p_S = \langle 0, \ldots, 1 \rangle, \tag{1}$$

where S is the size of the scanned fracture surface and S_0 is the size of the fracture surface projection into a base plane. With increasing segmentation of the fracture surface, the size of the criterial value p_S will probably be decreasing.

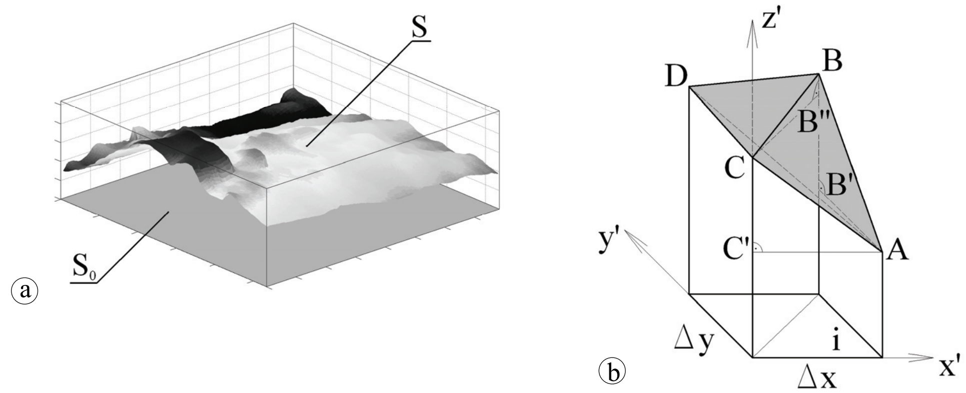

Fig. 6 (a) Area of fracture surface and (b) surface element of fracture surface

The network of equidistant points with the step Δx along the length and the Δy along the thickness represents the digitized model of the fracture surface (Fig. 6b). The area size of the surface defined by ABDC points can be approximately calculated upon its division into two triangles. The entire projection of the fracture surface is therefore divided into triangles (Fig. 7). The area of fracture surface above one triangle is determined by relevant ordinates of the height of the fracture surface, and according to Fig. 6b, the area of ABC triangle is calculated from the Heron formula,

$$S_i = \sqrt{s(s-|\mathrm{AB}|)(s-|\mathrm{AC}|)(s-|\mathrm{BC}|)}, \; s = \frac{|\mathrm{AB}|+|\mathrm{AC}|+|\mathrm{BC}|}{2}, \tag{2}$$

where the length of | AB | side is calculated from the ABB ' triangle

$$|\mathrm{AB}| = \sqrt{|\mathrm{AB'}|^2 + |\mathrm{BB'}|^2}, \tag{3}$$

the length of |AC| is calculated from the ACC' triangle

$$|\mathrm{AC}| = \sqrt{|\mathrm{AC'}|^2 + |\mathrm{CC'}|^2} \text{ and} \tag{4}$$

the length of |BC| is calculated from the CBB" triangle

$$|BC| = \sqrt{|CB''|^2 + |BB''|^2} \text{ and } |CB''| = \sqrt{\Delta x^2 + \Delta y^2} . \quad (5)$$

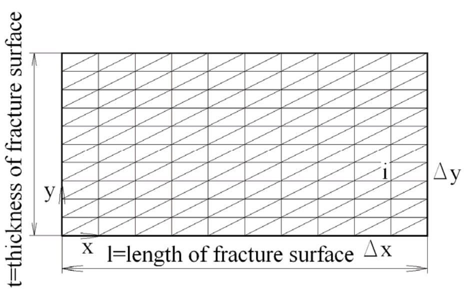

Fig. 7 Triangles on the surface projection of fracture area

The total fracture surface area is obtained by the sum of areas of all triangles positioned on the fracture surface

$$S = \sum_{i=1}^{N} S_i , \quad (6)$$

where N is the number of triangles covering the fracture surface, and the surface projection of the fracture surface is calculated from the rectangle area

$$S_0 = l\, t , \quad (7)$$

where l is the length and t is the thickness of the fracture surface. Generally the ABC and BCD triangles can be replaced with ABD and ACD ones to obtain a different size of the surface. Performed numerical calculations show that the effect of such a replacement is, at the assumed density of the network almost negligible.

4 RESULTS OF NUMERICAL SIMULATION

The proposed dimensionless areas ratio criterion was calculated for eighteen X70 steel DWTT specimens designed for the production of piping systems. The specimens were made for two thickness options, namely 15.7 mm and 18.7 mm and were tested at -20 °C. The DWTT test process and the PDF evaluation were conducted as prescribed in the API RP 5L3 [3] recommendation. The determination of the PDF was carried out directly on the specimen with the fracture surface, as given in Article 7.5c of this recommendation. The PDF was determined by two independent expert evaluators and has shown that the PDF values may significantly differ in some cases (see last two columns in the Table 1).

The areas ratio calculation was done based on the fracture surface length reduced by the notch depth and two thicknesses of the specimen, as it is provided in the API RP 5L3 recommendation, and the thickness is taken from the narrowest point of the scanned specimen. Digital models of the fracture surface, which correspond with the fractured specimen upon conducting a visual inspection, have been created for all DWTT specimens. A digital surface model of the fracture surface was replaced by a continuous model from the areas.

The dimensionless areas ratio criterion was established for three areas of the PDF assessment (see the comments below the Table 1). The value of this criterion will not change if the size of the measured area will be limited in length bounded by the depth of the notch. However, the reduction of the fracture surface by the double of the specimen thickness makes the areas ratio criterion already quite different.

Fig. 8 shows two scanned fracture surfaces for specimens with different PDF determined visually. Fig. 8a shows the value of PDF = 65 %, or 70 %. Fig. 8b shows PDF = 95 %. As expected, the dimensionless criterion areas ratio reaches higher values on the specimen with a lower PDF shown on Fig. 8a compared to the specimen with a higher PDF. Fig. 9 shows appearance of digitized fracture surface on two specimens with the 15.7 mm thickness. The dimensionless areas ratio criterion, p_S, for these specimens behaves in an analogical way to the previous case.

For the selected specimens with a lower thickness there is a 25 % difference between the PDF determined by independent evaluators. For thicker specimens the proportion reaches 27.5 %. The dimensionless areas ratio criteria, p_S, are significantly different for the specimens with a smaller thickness compared to the thicker specimens. Generally it seems to be a smaller difference between the highest and the lowest height of roughness on the fracture surface of the specimens with a lower thickness compared to the thicker specimens.

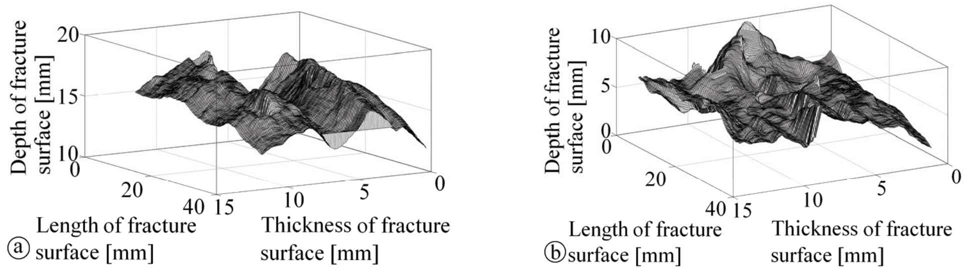

Fig. 8 Digitized fracture surface of (a) specimen no. 13 and (b) specimen no. 2

Table 1 Dimensionless areas ratio criterion and the results of subjective PDF evaluations by two independent evaluators

Test no.	**Specimen**	**Thickness** [mm]	p_S [-]	p_S* [-]	p_S** [-]	**PDF** [%]	**PDF** [%]
1	132766	15.7	0.604	0.585	0.661	95	95
2	132565	18.7	0.582	0.589	0.639	95	95
3	133222	18.7	0.523	0.534	0.626	90	90
4	132574	18.7	0.542	0.536	0.569	85	95
5	132309	18.7	0.698	0.703	0.631	80	85
6	128499	15.7	0.634	0.639	0.664	90	75
7	130661	18.7	0.663	0.672	0.650	75	85
8	130705	18.7	0.584	0.601	0.634	85	70
9	130663	18.7	0.674	0.693	0.687	60	85
10	132765	15.7	0.601	0.622	0.574	80	65
11	130729	18.7	0.629	0.644	0.652	65	80
12	130072	15.7	0.667	0.678	0.661	80	60
13	130697	18.7	0.607	0.628	0.624	65	70
14	132573	18.7	0.605	0.620	0.638	70	60
15	130699	18.7	0.657	0.654	0.657	70	55
16	133718	18.7	0.594	0.649	0.653	65	60
17	130645	18.7	0.602	0.613	0.592	70	50
18	127074	15.7	0.729	0.728	0.699	50	50

The dimensionless areas ratio criterion, p_S*, is given fracture surface when not reduced in its length for the depth of the notch. Similarly, p_S** is set for a potential situation when the fracture surface is reduced for the depth of the notch.

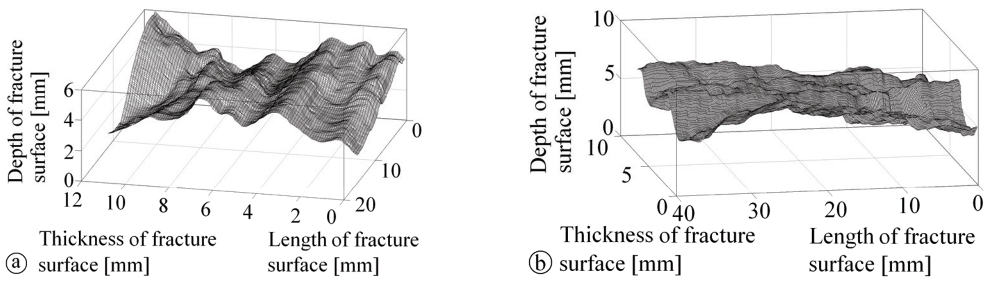

Fig. 9 Digitized fracture surface of (a) specimen no. 12 and (b) specimen no.1

In the investigated specimen set compiled from two thickness options the sufficient correlation between the dimensionless areas ratio criterion and the PDF determined by independent evaluators has not been found for smaller differences between PDF on the fracture surface. This discrepancy is probably caused by a miscalculation of the PDF by independent evaluators. To increase the sensitivity of the newly proposed dimensionless areas ratio criterion, p_S, its combination with other criteria would be appropriate.

5 CONCLUSIONS

The solution has identified a method for digitizing the fracture surface. Evaluation of the PDF to the fracture surface of fractured DWTT specimens has been newly proposed. The proposal of the digitized model of fracture surface was approximated with sufficient precision using a set of spatially oriented triangles. This approximation was successfully applied to a set of 18 fractured DWTT specimens produced from thickness of 15.7 mm and 18.7 mm of steel X70 sheets. In addition to the standard methods used for the PDF subjective monitoring the criterion values of the proportion of fracture surface projection and the size of the actual fracture surface of a digitized image were determined on fracture surfaces. It was found that the newly proposed criterion is, compared with the standard methods used for PDF evaluation, highly sensitive. For its technical application it requires the supplementation of the results of other methods.

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