The Nondimensional Plasticity Rotational Parameter used in DWT Tests: Evaluation by means of Finite Element

Andrea FONZO[1(*)], **Pietro SALVINI**[1], **Massimo DI BIAGIO**[2]

[1]University of Rome “Tor Vergata”, Dept. of Mechanical Engineering,Via del Politecnico n. 1,
00133 Rome ITALY, (fax: +39-06-2021351)
[2]Centro Sviluppo Materiali S.p.A., Via di Castel Romano n. 100,
00128 Rome, ITALY, (fax: +39-06-5055452)
E-mail addresses: fonzo@ing.uniroma2.it (A. Fonzo), salvini@uniroma2.it (P. Salvini),
m.dibiagio@c-s-m-it (M. Di Biagio)

Keywords: Ductile Fracture, Drop Weight Tear Test, Finite Element Simulation, Nondimensional Plasticity Rotational Parameter.

Abstract

The nondimensional plasticity rotational parameter, providing information on the effective location of the instantaneous centre of rotation, is very useful when evaluating material toughness in terms of Crack Opening Displacement or Crack Tip Opening Angle by means of Three Point Bending specimens. In the scientific literature there is a wide availability of empirical formulae for its estimate. Here a new approach is proposed, based on the use of a Finite Element code allowing a *step by step* estimate of the main kinematical parameters during the specimen rupture. Empirical and numerical results are compared and an analysis of the effect of main simulation parameters on the value of the nondimensional plasticity rotational parameter is performed.

Introduction

Drop Weight Tear Test is widely used to characterise the steels employed in gas pipeline manufacturing in the attempt to evaluate their response to ductile fracture propagation under high dynamics. This test allows to measure the whole energy consumed to completely fracture a notched specimen and one of its attractive points is represented by the opportunity to handle full thickness SENB specimens with extended ligaments, achieving the conditions of stable crack propagation. In last years many researchers (Demofonti et al. [1]) have developed specific procedures for material characterisation using laboratory tests on SENB specimens: the main aim is to establish whether the material toughness is higher than the minimum fracture resistance required to prevent stable propagation of ductile fractures.

The University of Rome “Tor Vergata” and the Centro Sviluppo Materiali S.p.A. have jointly developed a Finite Element code, based on an explicit solutor [2], named PICPRO *(Pipe Crack PROpagation code)*, that allows to perform numerical analyses of fracture propagation on pipelines and on whatever kind of specimens. The code gives the opportunity to evaluate fracture and kinematical parameters after fitting experimental load vs. time curves ([3]-[7]). One of the interesting kinematical parameters is represented by the nondimensional plasticity rotational parameter r* that accurately locates the effective centre of rotation (C) of the specimen during its rupture. More precisely it represents the ratio between the distance (d_{C-TIP}) of the instantaneous centre of rotation from the crack tip (P) and the residual ligament length (W-a) or, in other words, the distance between the crack tip and the instantaneous centre of rotation, calculated in the direction of specimen symmetry axis, normalised with respect to the residual ligament length; a schematic representation of r* is given in Fig. 1, where (a) indicates the actual crack length and (θ) the specimen rotation angle. Therefore it can be easily calculated as follows:

$$r^* = \frac{d_{C-TIP}}{W-a} \tag{1}$$

[(*)] *Corresponding author*

In the literature there is a wide availability of empirical formulae that allow to calculate the value of r* as a function of the actual crack size. However, none of them is able to account of its variability during crack advance, thus affecting fracture analysis application. The different approach here proposed for r* calculation is based on the use of PICPRO: numerical analyses presents the opportunity to calculate, *step by step,* the actual value of the nondimensional plasticity rotational parameter and a comparison with the current empirical solutions has been outlined.

The fracture model implemented into PICPRO

PICPRO makes use of a fracture model based on a cohesive layer, where a gradual nodal release is performed, to simulate the processes occurring inside the fracture process zone (FPZ) where new surfaces form, as a consequence of crack advance. The best fitting of experimental results, expressed in terms of load force (measured in correspondence of the impacting hammer) versus time, allows the set-up of the main parameters characterising the FPZ, needed to correctly simulate the fracture surface formation and the mechanisms involved. Once the critical value of the fracture-characterising parameter is established by laboratory tests, the optimal fitting is achieved by appropriately choosing the size Δ of FPZ to be used in numerical simulation, that is to say the length of the cohesive layer ([4],[6]). This parameter is not a meaningless mathematical number but is directly responsible of the amount of energy consumption inside the FPZ occurring during crack surface formation. The procedure is completely smart and allows to reach a very good accordance between experimental and numerical results ([7], [8]). In this work, the fracture parameter used to characterise the resistance opposed by the material to fracture propagation is the Crack Tip Opening Angle, that can be defined as the angle emerging from the opening crack flanks. Indicating with x the distance from the crack tip of a generic material point located on crack path, oriented towards crack propagation direction, CTOA can be calculated as the limit applied to the incremental increase of Crack Opening Displacement (COD) versus crack growth: The actual value of Crack Tip Opening angle ($CTOA_A$) is so given by:

$$CTOA_A = \lim_{x \to 0^-} \left\{ 2 \cdot \arctan \left[\frac{1}{2} \frac{\Delta}{\Delta a} COD\left(x\right) \right] \right\} \tag{2}$$

This parameter is quite useful since it well describes the geometrical aspect of the specimen in the region near the crack tip and it can be easily used when performing a finite element simulation. Moreover, according to many researchers ([9]-[11]) it well represents the material resistance opposed to fracture propagation.

In this circumstance crack advance has been managed using the Free fracture Propagation Algorithm (FPA), implemented into PICPRO, entirely able to simulate fracture process both in stable and in transient regimes [8]. During code execution, FPA perform a *step by step* test to establish whether critical fracture conditions are reached or not: more precisely it compares the actual value of the fracture-characterizing parameter (e.g. $CTOA_A$) and the corresponding critical value (e.g. $CTOA_C$); crack advance can take place only when the applied value exceeds the critical one, remaining completely still when such condition is no long-established. This algorithm is very helpful because it allows to use PICPRO on whatever type of specimens, being its use not limited to DWT Test simulation.

Comparison of PICPRO results with the empirical solutions available in literature

The nondimensional plasticity rotational parameter is used for the calculation of the plastic component of the crack opening displacement (COD) measuring the plastic displacement with a clip gauge positioned at the crack mouth during a DWT Test. Moreover, its knowledge is essential when using kinematical models for evaluation of $CTOA_C$ from the propagation energy absorbed for the complete rupture of Three Point Bending specimen. In the case of the kinematical model proposed by Martinelli et al. [12] $CTOA_C$ can be estimated using the following simplified equation, where the necessity to take advantage of r* is evident:

$$CTOA_C = 2\,\mathrm{arctg}\left[\frac{4 \cdot r^* E_P}{A^* \sigma_0 B \left(W - a_0\right)^2} \right] \tag{3}$$

where:

A : parameter dependent on specimen geometry (4/3 in case of SENB);*

σ_0 : *material flow stress equal to* $0.65\cdot(\sigma_S+\sigma_R)$*, where* σ_S *is the tensile proportional limit and* σ_R *is the ultimate tensile stress;*
E_P : *energy absorbed only for fracture propagation (related to the complete specimen rupture).*

The nondimensional plasticity rotational parameter used in the kinematical model for the estimate of $CTOA_C$ by mean of (3) is r* = 0.45. More precisely Venzi et al. [13] proposed the following table of value for r*, expressed as a function of the ratio (a/W):

a/W		***r****	***a/W***		***r****	***a/W***		***r****	***a/W***		***r****
0.05	→	1.359	0.30	→	0.475	0.55	→	0.448	0.80	→	0.439
0.10	→	0.642	0.35	→	0.466	0.60	→	0.446	0.85	→	0.438
0.15	→	0.546	0.40	→	0.460	0.65	→	0.444	0.90	→	0.437
0.20	→	0.508	0.45	→	0.455	0.70	→	0.442	0.95	→	0.436
0.25	→	0.488	0.50	→	0.451	0.75	→	0.441			

In the following, values of r* recommended by some national Standards are reported:
British and Australian Standards, [14] and [15] : r = 0.40;*
Chinese Standard, [16] : r = 0.45;*
Russian Standard, [17] : r = 0.50.*

Besides previous recommendations, a theoretical calculation of r* has been carried out using the slip-line theory [18] giving the values reported below, as a function of a/W (a is the actual crack length and W is specimen width):
(a/W) = 0.2 → r = 0.455;*
(a/W) = 0.4 → r = 0.447;*
(a/W) = 0.6 → r = 0.439.*

Another important work has been carried out by Matsoukas et al. [19] that proposed a linear relationship (4), whose fitting is tuned on AS1204–350 and AS1405–180 steels for manufacturing the DWTT specimens for laboratory tests:

$$r^{*}=0.463+0.04\cdot\left(\frac{a}{W}\right)\qquad \text{for}\ \left(\frac{a}{W}>0.18\right) \tag{4}$$

Matsoukas et al. proposed to increase the r* value, adopted in the Australian Standard, from 0.40 to 0.46. A numerical analysis by means of PICPRO has been here performed on DWTT specimen having the same dimensions of that used by Matsoukas [19] for extrapolating (4), which are reported below:
Thickness → s = 25.0 mm;
Width → W = 50.0 mm;
Length → L = 230.0 mm.

AS1405–180 steel was considered within all simulations performed. The results obtained are reported in Fig. 2 in terms of the nondimensional plasticity rotational parameter r* as a function of the ratio (a/W), where (a) indicates the actual crack length and (W) the specimen width. By comparison with the formula of Matsoukas (4) it is evident that the value of r* calculated by PICPRO is higher for any value of the ratio (a/W) considered. The averaged value calculated by PICPRO is slightly higher that 0.5, very close to the one proposed by the Russian Standard. The other Standards taken into consideration propose values very far from 0.5. Moreover differences between numerical results and those inferred using Matsoukas formula are consistent (about 10%).

Investigation on the effect of main test parameters on the plastic rotational parameter

A further analysis has been performed in the attempt to study the effect of the main kinematical and fracture parameters on the value of the plasticity rotational parameter. Simulations, carried out using the Free fracture Propagation Algorithm of PICPRO, have been performed on Standard DWTT specimens with dimensions according to the recommendation provided in the Italian Standard UNI EN 10274 (November 2000), [20]. The dimensions of the specimen are reported below:
Notch Depth → a_0 *= 10.0 mm;*
Thickness → s = 12.40 mm; (if not differently specified)
Width → W = 76.0 mm;
Length → L = 317.5 mm.

The material used was an API GRADE X80 steel (E_T = 190 GPa; σ_S = 610.0 MPa; σ_R = 760.0 MPa) with a $CTOA_C$ = 7.0° and a FPZ size of 7.5 mm. PICPRO takes into account also the effects on stress distribution of the strain rate by means of Cowper-Symonds model [21]. Nevertheless many parameters have been varied to investigate their effect on r*. In this paper it has been considered the effect of FPZ size (Fig. 3), $CTOA_C$ (Fig. 4), steel grade (Fig. 5), specimen thickness (Fig. 6) and impact hammer speed (Fig. 7). The results obtained show an evident insensitivity of r* value from these parameters, both when dealing with parameters related with the material and those associated with the kinematics of the test. Having just considered the insensitivity to thickness change, it is evident that the geometrical dimensions of the specimen (W and L) can heavily affect the value of r*. Finally it has been verified, to validate the finite element model used for the specimen, the independence of r* on the mesh size (Fig. 8). On the other hand, it is noteworthy that the averaged value calculated using PICPRO for the rupture of a specimen with the dimensions used by Matsoukas [19] is lower than the one which refers to the standard specimen recommended by Standard UNI EN 10274 (Fig. 9).

Conclusions

PICPRO represents an appropriate and alternative tool to calculate kinematical parameters in a Drop Weight Tear Test, helping in the comprehension of the fracture process and related material properties. Particularly its use has provided a valid support in the calculation of r*, allowing to check the validity of the r* values proposed in the literature. From a sensibility analysis performed using PICPRO it can be deduced that r* is not dependent on material characteristics (grade, FPZ size, $CTOA_C$) and some kinematical or geometrical parameter (impacting hammer speed and specimen thickness). Nevertheless its value appears to be heavily affected by the other specimen dimensions, such as L and W. Therefore it is strongly recommended to review the value of r* commonly used taking in mind such results.

References

[1]. Demofonti G., Buzzichelli G., Venzi S., Kanninen M. *Step by step procedure for the two specimen CTOA test*, Proc. of the 2nd International Conference on Pipeline Technology, vol. II, Ostend, Belgium, 11–14 September, 1995.

[2]. Belytschko T., Lin J.I., Tsay C.S. *Explicit algorithms for non-linear dynamics of shells*, Computer methods in applied mechanics and engineering, Vol. 42, pp. 225-251, 1984.

[3]. Berardo G., Salvini P., Di Biagio M. *Application of cohesive model to dynamic ductile fracture tests*, XIII European Conference on Fracture, Elsevier, San Sebastian, Spain, 2000.

[4]. Salvini P., Berardo G., Demofonti G., Mannucci G. *A Fracture Process Zone model for CTOA analysis*. Int. Conf. On Fracture Damage Mechanics 1999, Queen Mary & West field College University of London, London, United Kingdom, 27 - 29 July 1999.

[5]. Salvini P., Berardo G., Demofonti G., Mannucci G. *Numerical model of backfill constraint effect during crack propagation on buried large diameter gas pipelines*, Int . Pipeline Technology Conference, vol. I, 315-329, Brugge, Belgium, May 2000.

[6]. Salvini P., Fonzo A., Mannucci G. *Identification of CTOA and Fracture Process Parameters by Drop Weight Test and Finite Element Simulation*, Engineering Fracture Mechanics, 70/3-4, 553-566, 2003.

[7]. Fonzo A., Salvini P., Di Biagio M. *Fracture Propagation in DWT Back Slotted Specimens*, Proc. of International Congress on Fracture – Interquadrennial Conference, Moscow, Russia, June 21st – 27th, 2003.

[8]. Fonzo A., Salvini P., Di Biagio M., Mannucci G. *Full History Pipeline burst test through Finite Element Analysis*, International Pipeline Conference, Calgary, Alberta, Canada, September 29th – October 3rd, 2002.

[9]. Azodi D., Kalthoff J.F., *Evaluation of rapid crack propagation J-values for ductile steels*, Proc. of 4th Int. Conf. on Numerical methods in fracture mechanics, Freiburg, Germany, 23rd-27th April 1990.

[10]. Rice J.R., Sorensen E.P., *Continuing crack-tip deformation and fracture for plane-strain crack growth in elastic-plastic solids*, Journ. Mech. Phys. Solids, 26, 163-186, 1978.

[11]. Wang B., Yang W., Hwang K.C., *An engineering fracture parameter for non-J-controlled crack growth*, Fatigue Fract. Engng. Mater. Struct., 17/4, 469-477, 1994.

[12]. Martinelli A., Venzi S. *Tearing modulus, J-integral, CTOA and crack profile shape obtained from*

the load-displacement curve only, Engineering Fracture Mechanics, 53/2, pp. 263–277, 1996.

[13]. Venzi S., Martinelli A., Re G., Celant M. *Measurement of fracture initiation and propagation parameters from fracture kinematics*, In: Sih G.C., Mirabile M., editors. Analytical and Experimental Fracture Mechanics. Sijthoff and Noordhoff, Alphen aan den Rijn, The Netherlands, 737–756, Rockville, Maryland, U.S.A., 1981.

[14]. BS 5762. *Crack Opening Displacement (COD) Testing*, 1979.

[15]. AS 2205.7.3 *Crack Opening Displacement (COD) Test*. Standard Association of Australia, 1983.

[16]. Chinese Standard: GB 2358 – 80. Crack Opening Displacement (COD) Testing Method.

[17]. Robotnova Yu.N. (Editor), *New Method for Assessing the Resistance of Metals to Brittle Fracture (Russian translation)*, Mir, Moscow, 1972.

[18]. Alexander J.M., Komoly T.J. Journal of Mechanics and Physics 10, 265 – 275, 1962.

[19]. Matsoukas G., Cotterell B., Mai Y.W. *On the plastic rotation constant used in standard COD tests*, International Journal of Fracture 26, R49 – R53, 1984.

[20]. Norma UNI EN 10274, *Materiali metallici – Prova mediante caduta di massa*, Novembre 2000.

[21]. Cowper G.R., Symonds P.S. *Strain hardening and strain rate effects in the impact of cantilever beams*, Technical report no. 28 from Brown University, Providence, to the Office of Naval Research under Contract no. 562(10).

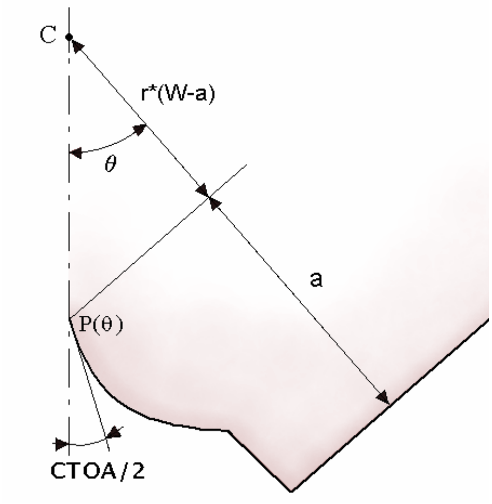

Fig. 1 – **Definition of the nondimensional plasticity rotational parameter in a DWTT.**

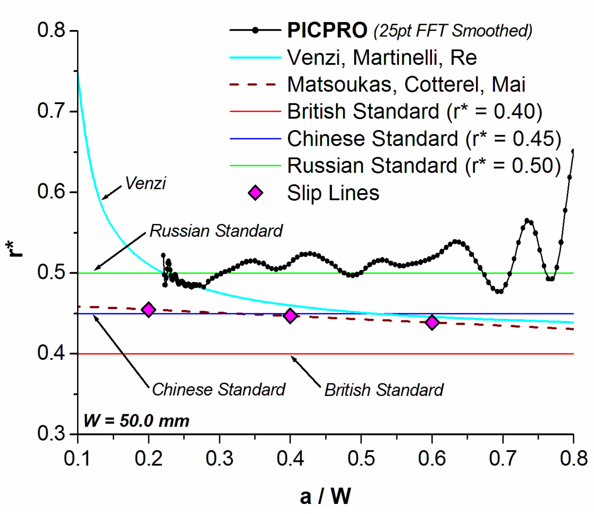

Fig. 2 – **Comparison of r* calculated with empirical formulae and with PICPRO.**

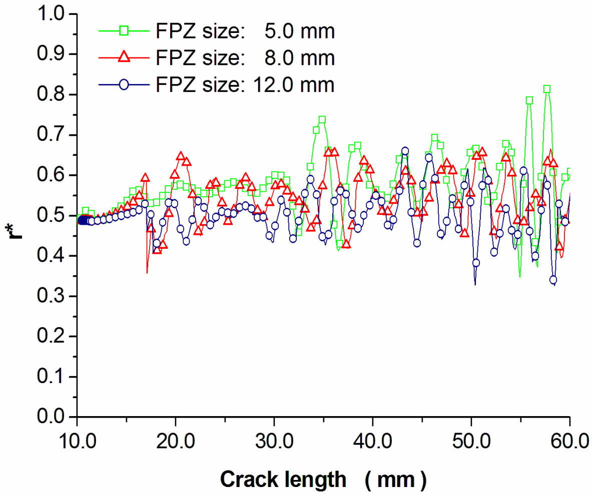

Fig. 3 – **Effect of FPZ size on r*.**

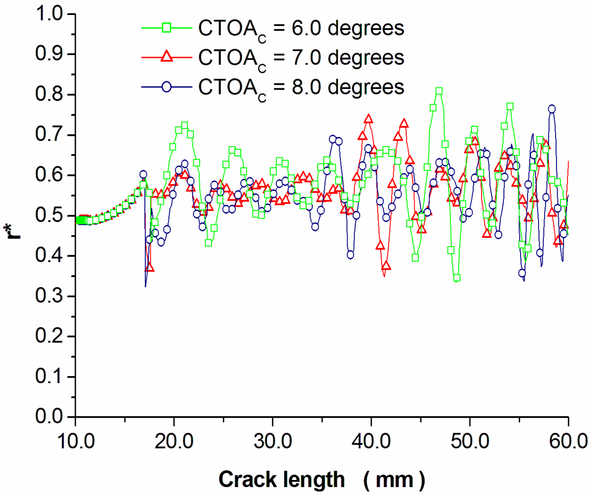

Fig. 4 – **Effect of CTOA$_C$ on r*.**

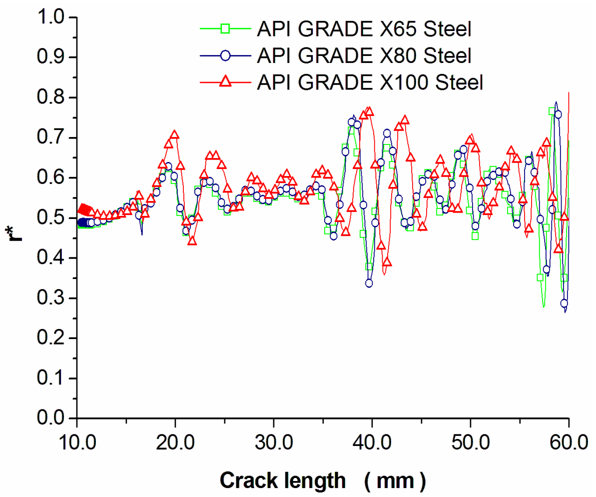

Fig. 5 – Effect of Steel Grade on r*.

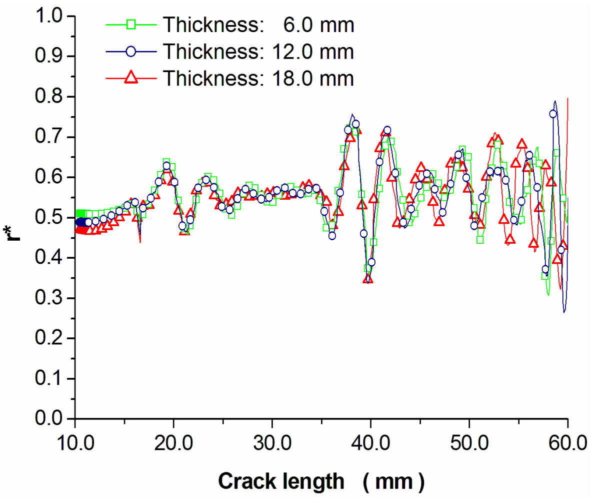

Fig. 6 – Effect specimen thickness on r*.

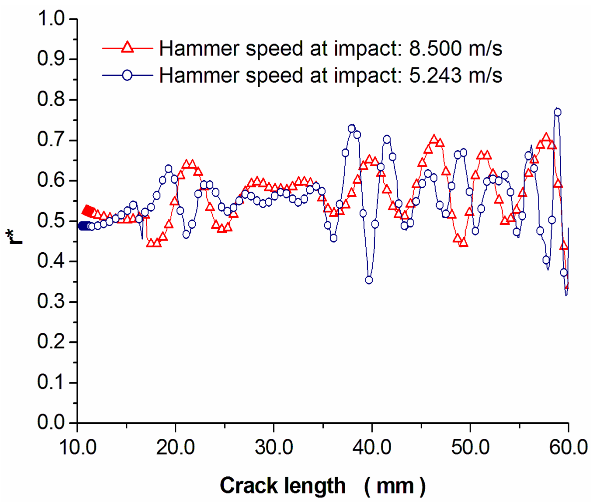

Fig. 7 – Effect of initial hammer speed on r*.

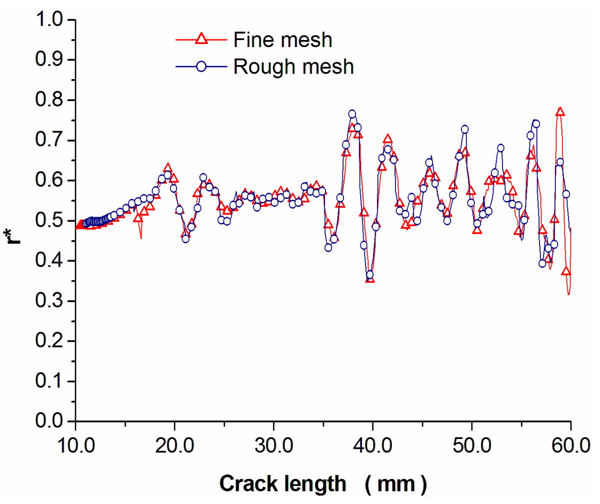

Fig. 8 – r* calculation: mesh insensitivity.

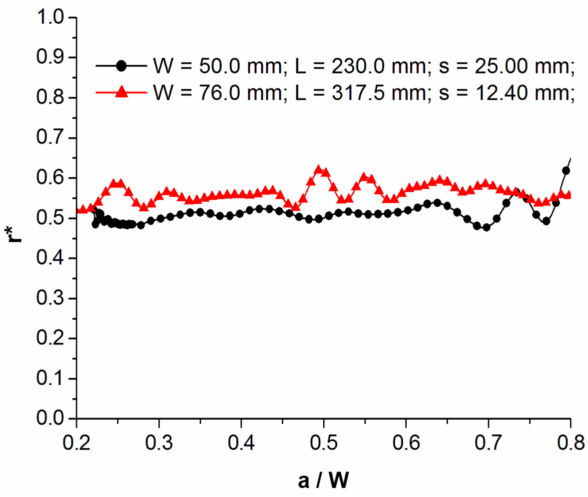

Fig. 9 – Effect of specimen size on r*.