Effect Of Stress Triaxiality On The Strain Concentration Factor

Hitham Tlilan, Mohammad Gharaibeh, Manal Mustafa, Ali Jawarneh

Abstract**:** ***Axisymmetric machine element with irregularities such as notches encountered with effects of stress triaxiality on the strain concentration factor (SNCF) at the reduced section. The effect of notch geometries on the triaxial stress state development in the critical section of a notched cylindrical bar is studied here using FEM. In addition, the effect of triaxial stress state (TSS) on the SNCF is evaluated. To this end, a notched cylindrical bars with notch depths from extremely deep notch ($d_o/D_o = 0.2$) shallow notch ($d_o/D_o = 0.95$) has been employed. The results show that the notches introduce a TSS at the critical section, which strongly affected by the notch depth as well as the notch radii. In this paper, a new concentration factor is introduced as the ratio of the stress triaxiality factor at the notch root (TF_{NR}) to the average triaxiality on the critical section (η), i.e. the triaxiality concentration factor K_{TF}. The numerical results reveal that the variation of the average triaxiality factor with total strain shows the same trend as that of the SNCF. The variation of the elastic values of TF_{CN}, , η, and SNCF with d_o/D_o and show that the minimum TF_{NR} leads to the maximum elastic SNCF. It is prominent that elastic TF_{NR} is less that elastic TF_{CN} for $0.2 \le d_o/D_o \le 0.85$, while it is greater for shallow notches. The current results indicate a strong compatibility between the newly defined triaxiality concentration factor and the SNCF up to general yielding.***

Keywords ***: Finite element method, Notch, Strain concentration, Stress triaxiality.***

I. INTRODUCTION

The machine elements are formed and used in applications such as structure and machines. In many application the machine elements contains irregularities such as holes, fillets , and notches. The presence of irregularities in the machine elements introduces a discontinuity in the cross section of the structural and machine elements that causes from a destruction or a fracture of such elements. Even in the steel construction fracture has been reported in the joints between steel columns and beams. The presence of any type of discontinuities causes a multiaxial stress state, which introduces stress and strain concentrations at the net or reduced cross section. As a result, a ductile crack is initiated and it breaks through the ductility limit of the material. This ductile crack leads to brittle fracture[1-10].

Due to programming and electronically applications developments, a variety of simulation and numerical techniques are employed for stress and strain calculations [11,13,14,15,17,28-32,39].It is significantly recognized that, due to irregularities the stresses and strains are localized and a TSS field exists in the vicinity of the irregularity's root. For any kind of irregularities, effects of geometrical properties of the machine element and irregularities such as notch depth, opening angle, root radius, the net and gross sections of the machine elements should be clarified. It has been concluded that it is difficult to obtain solutions for the stress and strain concentrations in the vicinity of the irregularity. The stress and strain concentrations for many types of irregularities as circular hole, surface and circumferential notches has been extensively studied under different types of loading. All of the published results confirm that the stress and strain concentrations are prominently affected by the irregularities geometers as well as the stress state at the critical section. However, most of the published researches concentrate on the stress concentration factor [1-26].

Recently, it has been proved that even if there is a uniaxial stress state at the gross section there is a triaxial stress in addition to that stress and strain concentrations. This high triaxial state of stress causes the notch strengthening of the notched machine elements [22, 24,28-32]. Moreover, for cylindrical bars the magnitude and the concave distribution of the longitudinal strain on the critical section has a prominent effect on the notch strengthening. Accordingly, it has been deduced that the strain concentration factor is more effective in predicting failure of the notch bars [14, 20-23]. This is basically attributed to the definition of the SNCF under TSS at the critical section. It has been proposed for improved understanding of strain concentration under different types of loading as well as various types of geometries. Based on careful results of the previous solutions of proposed strain concentration factor; a reasonable values has been obtained and be able to remove the discrepancy of the conventional definition to the longitudinal strain concave distribution [24, 28-32, 34-36, 39]. In literature; the effects of stress triaxiality on stress concentration has been extensively studied for a wide variety of irregularities under different types of loading.

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However, the effect of the stress triaxiality has not widely studied. In this paper, the effect of stress state has proposed to be studied on the newly defined strain con concentration factor under axial load of static tension.

II. STRAIN CONCENTRATION AND TRIAXIALITY FACTORS

A newly defined strain concentration factor has been recently introduced. This strain concentration factor has been defined under TSS and it is the ration of the longitudinal strain at the notch root to the nominal axial strain [24, 28-32, 34-36, 39]:

$$K_\varepsilon = \frac{(\varepsilon_z)_{\text{max.}}}{(\varepsilon_z)_{\text{nom.}}} \tag{1}$$

Where; $(\varepsilon_z)_{max}$ is the maximum axial strain, which is the longitudinal strain at the notch root at any level of load. is the nominal or the average longitudinal strain $(\varepsilon_z)_{nom}$ on the critical section is given by

$$(\varepsilon_z)_{\text{nom.}} = \frac{1}{A}\int_A \varepsilon_z \, dA = \frac{1}{\pi r^2}\int_r^{r_n} \varepsilon_z \; 2\pi r dr \tag{2}$$

It should be mentioned that the longitudinal strain occurs under triaxial stress state on the critical section. As a result, the newly defined strain concentration factor expresses the concave distribution of the longitudinal strain on the critical section at any level of deformation. Accordingly, the effect of the triaxial stress state should studied and clarified. To this end, the triaxiality concentration factor (K_{TF}) is introduced by the ratio of the notch root stress triaxiality $(TF)_{NR}$ to the average stress triaxiality (η) as follows:

$$K_{TF} = \frac{TF_{NR}}{(TF)_{\text{nom.}}} = \frac{TF_{NR}}{\eta} \tag{3}$$

Since the stress triaxiality is calculated at any location of the critical section at any level of deformation using the following equation;

$$TF = \frac{3\sigma_m}{\sigma_{eq}} \tag{4}$$

Where; $\sigma_m = \frac{\sigma_z + \sigma_r + \sigma_\theta}{3}$ is the Volumetric or Hydrostatic stress. The Von-mesis equivalent stress $= \sigma_{eq} = \frac{1}{\sqrt{2}}\sqrt{(\sigma_z - \sigma_r)^2 + (\sigma_r - \sigma_\theta)^2 + (\sigma_z - \sigma_\theta)^2}$.

The new triaxiality concentration factor (K_{TF}) is given by a new definition of the average stress triaxiality (η), i.e.:

$$\eta = \frac{1}{A}\int_r^{r_n} (TF)\, dA = \frac{1}{\pi r^2}\int_r^{r_n} \frac{3(\sigma_m)}{(\sigma_{eq})} 2\pi r dr \tag{5}$$

III. MATERIAL AND GEOMETRICAL PROPETIES

The geometries considered in this study are circumferential U-notches with different depths. The notch depth is given by the ratio between the net and gross diameter d_o and D_o, respectively. This ratio, i.e. d_o/D_o, has been varied from 0.2 to 0.95 by varying the critical section diameter while the gross diameter is kept constant of 1.67 cm. The length of each specimen is constant of 5.0 cm that enough to get the pure nature of the notch effects, as shown in Figure 1. Three notch radii of 0.5, 1.0, and 2.0 mm are employed in this study. The material used is An Austenitic Stainless Steel with yield strength and modulus of Elasticity of 245.9 MPa and 206 GPa, respectively.

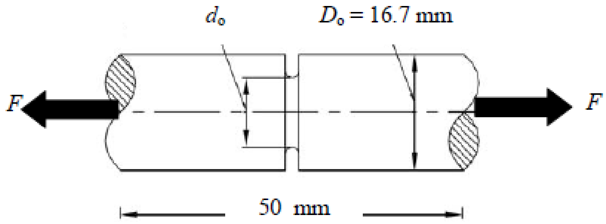

Fig. 1. Notched bars geometrical properties.

IV. FINITE ELEMEMNT METHOD MODELING

The triaxiality and strain factors of cylindrical bars with a circumferential notch are systematically investigated using finite element method. Due to symmetry; one quarter of the cylindrical bar has been modeled by Finite Element, as shown in Figure 2. All computations are carried out using the MSc. MARC and MATLAB code. The Finite Element meshes are assembled with an Axisymmetric ring, Isoparametric, and Quadrilateral element type 28 in MARC library. This element contains 8 nodes and 9 point Gaussian integration points with biquadratic interpolation and full integration. The minimum elements size is closed to the notch root and it becomes larger as the distance from the notch root gradually increases. These models represent a compatibility between the required level of mesh refinement to an accurate representation of the stress and strain fields in any level of deformations up to general yielding.

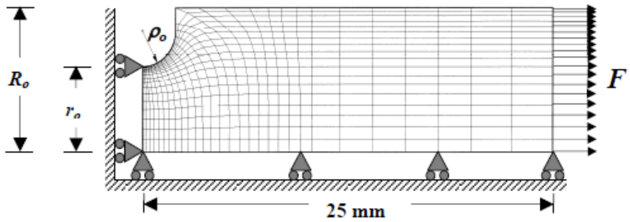

Fig. 2. Finite element model of the notched bar.

V. RESULTS AND DISCUSSIONS

A. Elastic strain-concentration factor

Define According to the simulation results, the stress triaxiality (*TF*) is calculated using Eq. (4) for deformation levels from elastic up to general yielding. Figure 3 shows the *TF* distribution on the critical section for all notches employed. It is prominent that *TF* distribution depends on the notch depth from the extremely deep to shallow notches at any level of deformation. The *TF* is maximum at the centriodal axis (r/r_n = 0.0) of the employed specimens of d_o/D_o = 0.2 ~ 0.5, while the maximum *TF* moves to be closed to the notch root (r/r_n = 1.0) for notches with $0.6 \le d_o/D_o \le 0.95$. Actually, the maximum *TF* is very closed to notch root for shallow notches; i.e. $0.8 \le d_o/D_o \le 0.95$.

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The effects of notch depth on the elastic SNCF, average triaxiality factor (η), *TF* at the center, and *TF* at the notch root are compared in Figure 4. It can be seen that *TF* values at the center decreases with increasing notch depth from extremely to shallow notches. On the other hand, *TF* at the notch root shows an increase with increasing notch depth to be the larger for shallow notches. Is clear also from the same Figure that the average triaxiality factor (η) increases from its value for extremely deep notch and reaches maximum value at deep notches , i.e. $0.3 \leq d_o/D_o \leq 0.5$, and then decreases with increasing decreasing notch depth to have minimum value at shallow notches. From the same it is prominent that within elastic deformation; the SNCF increases with decreasing notch depth for notch of $0.2 \leq d_o/D_o \leq 0.5$ and reaches its maximum at $d_o/D_o = 0.65$. As the notch becomes shallower the elastic SNCF decreases. Their elastic values decrease with the rapidly decreased η as the notch depth decreases. An empirical formulae had been obtained by fitting the FE simulation results as follows:

$$K_\varepsilon = K_o + K_1\left(\frac{d_o}{D_o}\right) + K_2\left(\frac{d_o}{D_o}\right)^2 + K_3\left(\frac{d_o}{D_o}\right)^3 + K_4\left(\frac{d_o}{D_o}\right)^4 + K_5\left(\frac{d_o}{D_o}\right)^5 \quad (6)$$

$$\eta = \eta_o + \eta_1\left(\frac{d_o}{D_o}\right) + \eta_2\left(\frac{d_o}{D_o}\right)^2 + \eta_3\left(\frac{d_o}{D_o}\right)^3 + \eta_4\left(\frac{d_o}{D_o}\right)^4 + \eta_5\left(\frac{d_o}{D_o}\right)^5 \quad (7)$$

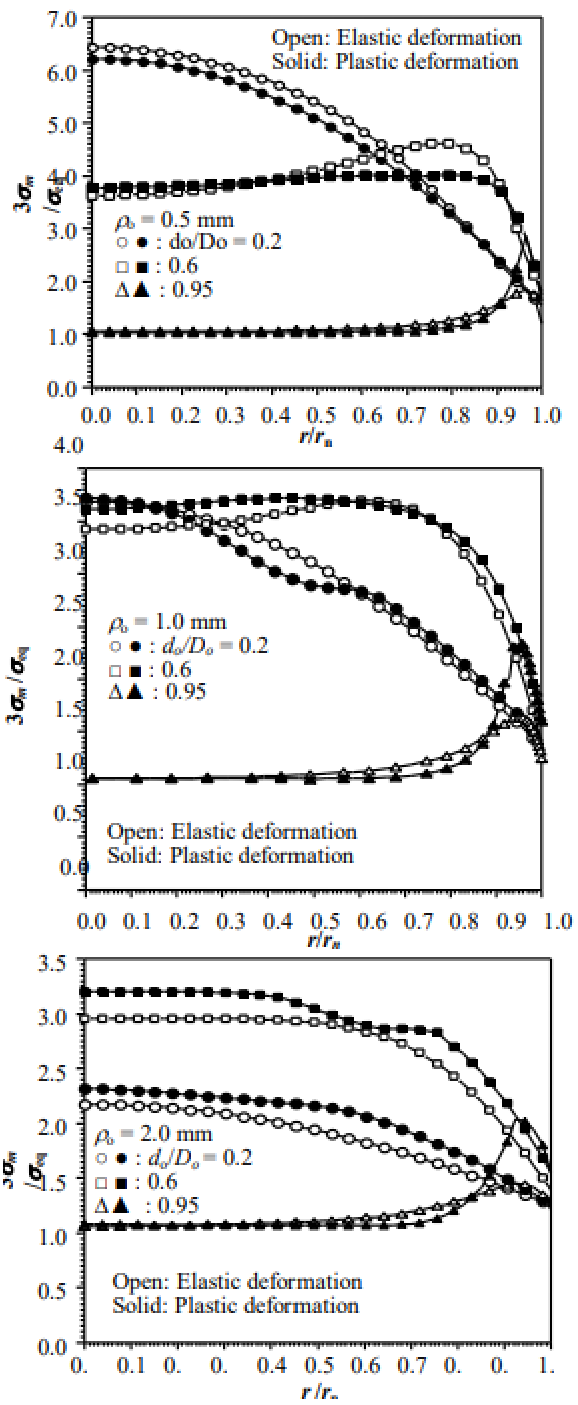
$$TF_{NR} = T_{ro} + T_{r1}\left(\frac{d_o}{D_o}\right) + T_{r2}\left(\frac{d_o}{D_o}\right)^2 + T_{r3}\left(\frac{d_o}{D_o}\right)^3 + T_{r4}\left(\frac{d_o}{D_o}\right)^4 + T_{r5}\left(\frac{d_o}{D_o}\right)^5 \quad (8)$$

$$TF_{CN} = T_{co} + T_{c1}\left(\frac{d_o}{D_o}\right) + T_{c2}\left(\frac{d_o}{D_o}\right)^2 + T_{c3}\left(\frac{d_o}{D_o}\right)^3 + T_{c4}\left(\frac{d_o}{D_o}\right)^4 + T_{c5}\left(\frac{d_o}{D_o}\right)^5 \quad (9)$$

The coefficients values for all equations and notches employed are listed in Tables 1, respectively.

The variation of elastic SNCF versus the average triaxiality (η) for different notch configurations was investigated. Figure 5 shows a prominent effect of the notch depth on the relation between the elastic SNCF and η. It is evident from that the elastic SNCF becomes larger with increasing η of notches with $0.2 \leq d_o/D_o \leq 0.4$. For $0.5 \leq d_o/D_o \leq 0.65$, we can see that as η decreasing, the elastic SNCF increases and reaches maximum value at $d_o/D_o = 0.65$. For shallower notches $0.7 \leq d_o/D_o \leq 0.75$ the decrease in η leads also to a decrease in the elastic SNCF. This is true for all notch radii employed.

In particular we have approve the hypothesis that, under uniaxial tensile load conditions, the longitudinal strain due to the notch has a concave distribution at the critical section and occurs under triaxial stress state. This means that SNCF is strongly affected by the triaxial stress state at the critical section [28-32, 34-36, 39]. To illustrate the relation between the triaxiality concentration factor and the strain concentration factor; both are plotted on Fig. 6. It is clear that there is an inverse relationship between them. Particularly, for deep notches $0.2 \leq d_o/D_o \leq 0.6$ the decrease in K_{TF} leads to an increase in K_ε. Conversely, as K_{TF} increases K_ε decreases for intermediate deep and shallow notches; i.e. $0.65 \leq d_o/D_o \leq 0.95$.Fig. 3. Triaxiality factor distribution on the net section



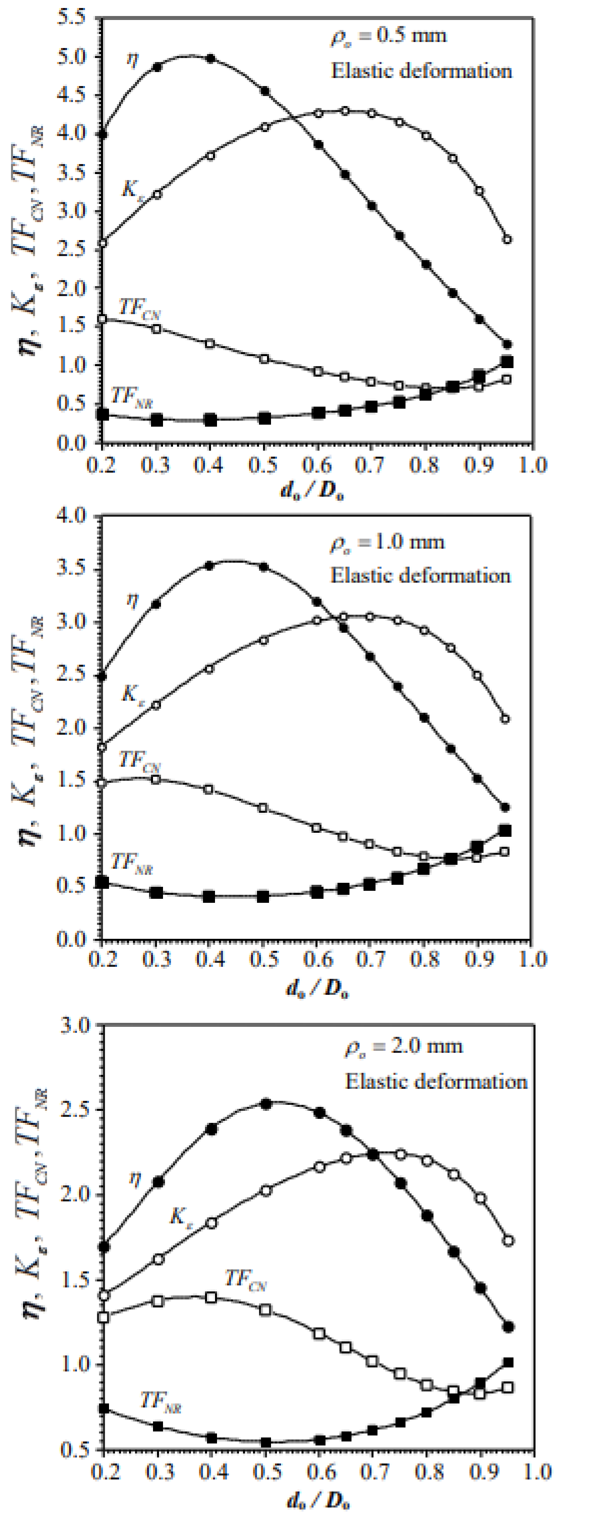


Fig. 4. Effect of notch depth on average triaxiality (□), strain –concentration factor ($K_□$), and triaxiality factor at the notch root (TF_{NR}) and at the center of the specimen(TF_{CN}).

B. Elastic –plastic strain-concentration factor

Use The influence of the notch geometries on the variation of average stress triaxiality (η) with true strain has been also studied. The true strain at the critical section given by:

$$\varepsilon_t = \ln\left(\frac{l}{l_o}\right) = \ln\left(\frac{A_o}{A}\right) = \ln\left(\frac{d_o}{d}\right)^2 = 2\ln\left(\frac{d_o}{d}\right)$$

However, consideration of plastic deformation of notched bars requires an in-depth understanding of the behavior of notched bars under large plastic strains. Accordingly, Figure 6 shows that the average triaxiality (η) is constant within elastic true strain ε_t. The notch with a larger d_o/D_o and larger notch radius lead to larger elastic ε_t strain range. This essentially attributed the development of plastic deformation from the notch root, which is starts at deep notches and smaller notch radius earlier than that for the shallow notches and larger notch radius. As the plastic ε_t develops from the notch root, η suddenly increased and reaches maximum value. After that, it gradually decreases for deeper notches; i.e. $0.2 \leq d_o/D_o \leq 0.6$, and notch radius of 0.5 and 1.0 mm. On the other hand, η suddenly decreases with increasing plastic ε_t for shallow notches $0.65 \leq d_o/D_o \leq 0.95$ and all notches employed.

Therefore, it is evident that the stress triaxiality strongly affected the strain-concentration even at very low deformation levels; i.e. elastic deformation. This effect becomes severer as the plastic deformation develops from the notch root. The current results of the newly defined SNCF shows a strong compatibility between the stress triaxiality and the fracture of the notch bars. This is due the presence of the strain concentration even at general yielding, while the conventional strain and stress concentration factors dropped to be less than unity immediately as the plastic deformation develops from the notch root. The current results show that new SNCF is strongly influenced by the degree of triaxial stress state at the critical section, while the stress and conventional strain concentration factor show contradiction to stress state especially at plastic deformation level.

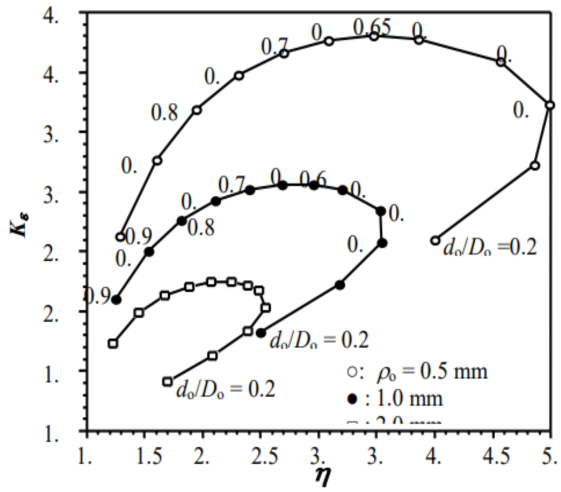


Fig. 5. Effect of notch depth on the variation of the strain –concentration factor (K_ε) with average triaxiality.

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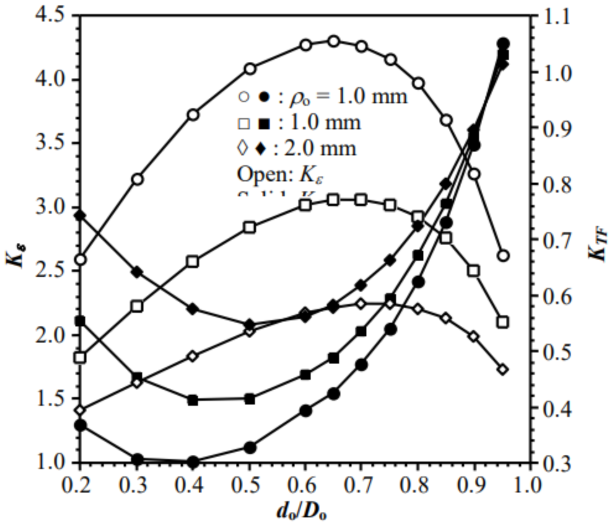

Fig. 6. Comparison of the effect of notch depth on the strain – concentration factor and triaxiality concentration factor.

VI. CONCLUSION

Using the finite element analysis, a notched cylindrical bars with different configurations subjected to axial tension have been investigated here. The effects of stress triaxiality on the strain concentration factor has studied and the following conclusion has been drawn:

1. The notch depth and notch radius have an apparent effects on the stress triaxiality factor, which is the highest in the smallest notch radius. For all notch radii employed the TF values at the center of the notched bar are the largest for d_o/D_o from 0.2 to 0.5. On the other hand, the maximum TF values becomes closed to the notch root for shallower notches, i.e. $0.60 \leq d_o/D_o \leq 0.95$.
2. The newly defined triaxiality concentration factor is introduced here, which is strongly affected by the notch geometry. It is concluded that even relatively small deformation levels introduce large strain concentration factor. The smaller triaxiality concentration factor leads to the larger SNCF.
3. It is exciting to note that even if the load is uniaxial; there is a prominent dependent of the SNCF not only on the geometrical properties but also on the stress state at the critical section.

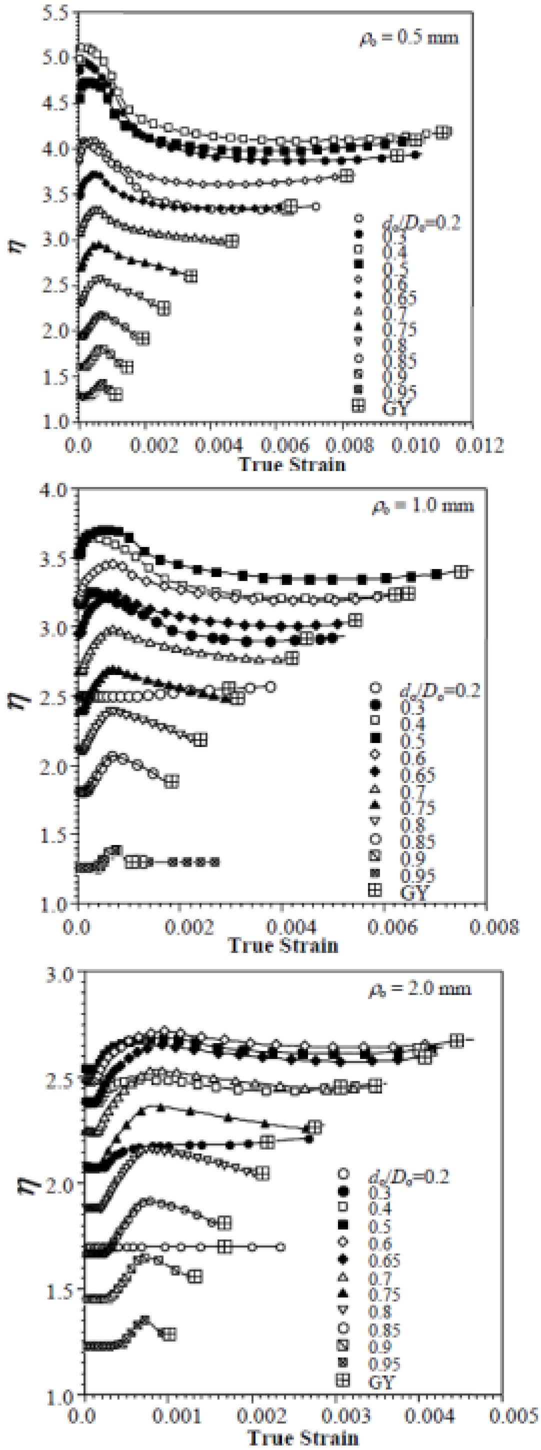

Fig. 7. Effect of notch depth on the variation of the average triaxiality (η) with true strain (ε_t).

Table I. Curve fitting coefficients.

ρ_o [mm]	$K_\varepsilon = K_o + K_1\left(\frac{d_o}{D_o}\right) + K_2\left(\frac{d_o}{D_o}\right)^2 + K_3\left(\frac{d_o}{D_o}\right)^3 + K_4\left(\frac{d_o}{D_o}\right)^4 + K_5\left(\frac{d_o}{D_o}\right)^5$					
	K_o	K_1	K_2	K_3	K_4	K_4
0.5	1.5687	1.7073	29.802	-78.616	82.06	-34.746
1.0	1.4574	-1.8509	29.585	-67.408	67.212	-27.459
2.0	1.3653	-2.6853	22.139	-46.453	45.879	-18.864

	$\eta = \eta_o + \eta_1\left(\frac{d_o}{D_o}\right) + \eta_2\left(\frac{d_o}{D_o}\right)^2 + \eta_3\left(\frac{d_o}{D_o}\right)^3 + \eta_4\left(\frac{d_o}{D_o}\right)^4 + \eta_5\left(\frac{d_o}{D_o}\right)^5$					
	η_o	η_1	η_2	η_3	η_4	η_5
0.5	-1.1409	39.673	-78.336	40.056	13.556	-12.869
1.0	1.3225	-0.03217	54.05	-149.45	141.32	-46.261
2.0	1.6899	-5.9281	45.043	-88.079	65.679	-17.393
	$TF_{cen.} = T_{co} + T_{c1}\left(\frac{d_o}{D_o}\right) + T_{c2}\left(\frac{d_o}{D_o}\right)^2 + T_{c3}\left(\frac{d_o}{D_o}\right)^3 + T_{c4}\left(\frac{d_o}{D_o}\right)^4 + T_{c5}\left(\frac{d_o}{D_o}\right)^5$					
	T_{co}	T_{c1}	T_{c2}	T_{c3}	T_{c4}	T_{c5}
0.5	0.9382	9.0164	-40.878	72.933	-63.064	22..025
1.0	0.4188	10.519	-34.47	48.502	-35.955	11.939
2.0	1.0033	0.8593	6.2271	-21.529	18.511	-4.1281
	$TF_{root} = T_{ro} + T_{r1}\left(\frac{d_o}{D_o}\right) + T_{r2}\left(\frac{d_o}{D_o}\right)^2 + T_{r3}\left(\frac{d_o}{D_o}\right)^3 + T_{r4}\left(\frac{d_o}{D_o}\right)^4 + T_{r5}\left(\frac{d_o}{D_o}\right)^5$					
	T_{ro}	T_{r1}	T_{r2}	T_{r3}	T_{r4}	T_{r5}
0.5	0.7683	-3.1991	6.9731	-4.4823	-1.8817	3.1065
1.0	1.056	-3.8957	8.4317	-8.2732	3.5902	0.3046
2.0	1.036	-1.631	0.173	4.1288	-4.8625	2.3159

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