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Finite Element Analysis of Twist Rate Role in High Pressure Torsion Process

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Abstract

The main goal of this work was to partially fill the existing knowledge gap concerning the twiste rate sensitivity of plain carbon steed severe plastic deformed by high pressure torsion(HPT) process. In this regard the twist rate effect on torque-twist angle curve, maximum torque and failure equivalent strain was investigated using finite element analysis (FEA) with Abaqus software. The mechanical properties, flow stress equation, initial pressure of 300 MP and five different twist rates from 0.5 rad/s to 4 rad/s were used as input data in the modeling of the HPT process. According to obtained results, the torque-twist angle diagram shifted towards lower values with increasing twist rate. The twiste rate sensitivity index was negative and depended on twist angle as $M = -0.018\varphi$. The modified Johnson-Cook equation was an excellent fit to the all torque-twist angle curves. The maximum torque and failure equivalent strain initially increased from 1177 to 1357 N.m and from 1.25 to 2.80, respectively, by increasing twist rate to 2 rad/s, and then decreased to1209 N.m and 2.63, respectively. The maximum value of failure equivalent strain obtained with FEA was 22%, 61% and 104% higher than the values calculated using von Mises, modified Hencky and Degtyarev equations, respectively.

Keywords: HPT; Twist rate; FEA; Torque, Equivalent strain; Johnson-Cook model.

1. Introduction

High-pressure torsion (HPT) is a severe plastic deformation (SPD) which has recently received considerable attention because, it is capable of producing higher equivalent strains in metallic materials, thereby generating finer microstructures (down to several nanometers) as well as compacting fine particles and amorphous ribbons. Over the past 25 years, extensive research has been conducted on this process and its effects on microstructure and material properties; notable results are summarized in review articles [1,2].

The principle of HPT is based on placing a small cylindrical sample between two dies, as illustrated in Figure 1, applying high pressure on the sample surface via the upper die, and rotating the dies relative to each other. The applied pressure generates significant friction between the sample and die surfaces, lead to applying shear stresses exceeding the material's yield strength and producing shear strain (γ) which its maximum value can be calculated as [2]:

$$\gamma = \frac{r\varphi}{h} \quad (1)$$

where h and r are height and radius of sample, respectively, and φ is a torsion angle

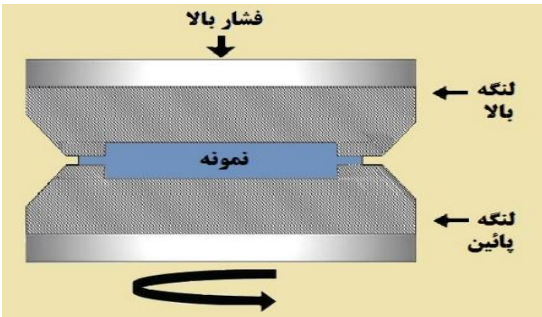

Figure 1 . Schematic of constrained high-pressure torsion

The strain rate $\varepsilon^{\circ} = (d\varepsilon/dt)$ is one of the key variables affecting the behavior of metals during severe plastic deformation. Typically, as the strain rate increases, the material's yield stress increases, the strain corresponding to necking decreases, and the material becomes more brittle [3]. However, inverse (negative) behavior and the existence of a critical strain rate marking a transition from negative to positive effects have also been reported [4]. A review of the literature indicates that, to date, the sensitivity index of steels to torsion rate in HPT has not been systematically studied. The present work is the first quantitative investigation in this regard, aiming to fill part of this knowledge gap.

2- Materials and Methods

The finite element analysis was performed using Abaqus 2024 with the explicit solver. A cylindrical sample of plain carbon steel with two end caps (Fig. 1a) was mesed with meshed with 6,864 C3D8R elements (Fig. 2b). The mechanical properties, flow stress equation, initial pressure of 300 MP and five different twist rates from 0.5 rad/s to 4 rad/s were used as input data.

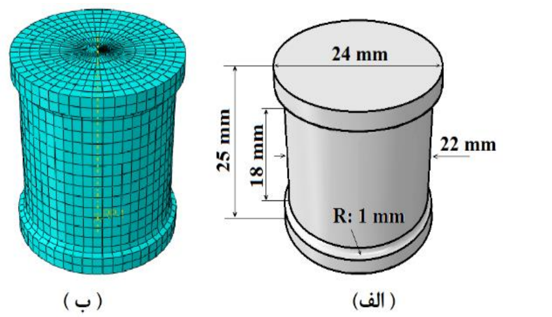

Figure 2 . Geometry and dimensions of the specimen used: (a) before meshing, and (b) after meshing and prior to the HPT process.

3- Results and Discussion

Figure 3 presents the variation of torque with twist angle at different twist rates. It is observed that the maximum torsional torque initially increased from 1177 N·m to 1357 N·m as the twist rate increased up to 2 rad/s, and then decreased to 1209 N·m.

The twist-rate sensitivity index M is defined as follows [5]:

$$M = (\partial log\omega / \partial log\omega)_{\varphi} \tag{2}$$

As shown in Fig. 4 the log (torque) varied linearly with log (twist-rate) with a negative slope for a fixed twist angles. The index M was a linear function of the twist angle according to Equation 3 and shifted toward more negative values with increasing twist angle:

$$M = -0.018\varphi \tag{3}$$

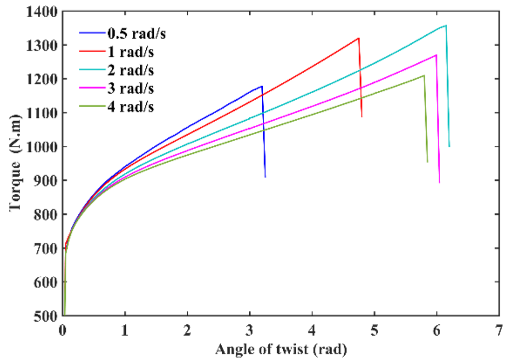

Figure 3 . Variation of torsional torque with twist angle at different twist rates.

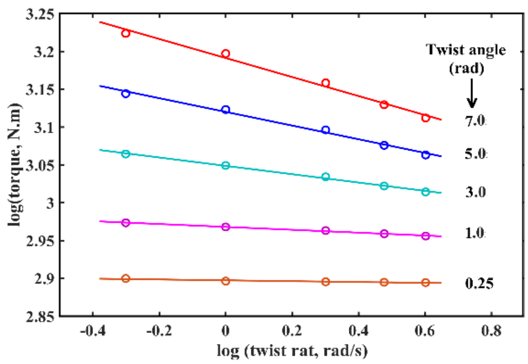

Figure 4 . Variation of log(torsional torque) with log(twist rate) at several different twist angles

In order to deriving a model for the material's plastic deformation one can assume that the material behavior is described by one of the previously proposed models [6] and then evaluate it. Here we assume that the material behavior under the HPT process follows the Johnson–Cook model in the following general form:

$$T_q = f(\varphi)(1 + Mln\omega) \tag{4}$$

In this formulation, $f(\varphi)$denotes the strain-hardening function of the material, which can be determined at a unit twist rate. Within the original Johnson–Cook model, this function is defined as $f(\varphi) = A + B\varphi^Q$, commonly referred to as the Ludwik equation. By fitting this relation to the torque–twist angle curve corresponding to a twist rate of 1 rad/s, the constants A, B, and Q were determined to be 722, 191, and 0.694, respectively. For twist rates of 0.5 rad/s 4 rad/s, the curves obtained from Eq. (4), incorporating the Ludwik strain-hardening function, were compared with the finite element simulation results (Fig. 5a). As illustrated, the level of agreement between the predicted and simulated results is unsatisfactory. Instead, when the Ludwik equation was replaced by an exponential relation analogous to the model proposed by Chen et al. [50], excellent agreement between the model and experimental results was obtained, as can be seen in Figure 5b.

$$f(\varphi) = a\exp(b\varphi) - c\exp(-e\varphi) \quad (5)$$

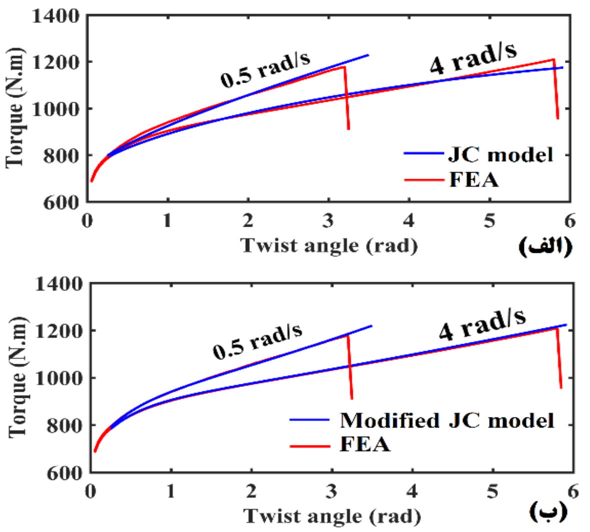

Figure 5 . Comparison of finite element analysis (FEA) results with models: (a) Johnson–Cook model, (b) Modified Johnson–Cook model

In Figure 6, the equivalent strain values obtained by FEA at different twist rates are compared with those calculated using Equations 6 (von Mises), 7 (modified Hencky) and 8 (Dakhtyarov) [7,8]. As seen the values calculated using the von Mises relation are closer to the FEA results

$$\bar{\varepsilon} = \frac{\gamma}{\sqrt{3}} + \ln(\frac{h_o}{h}) \quad (6)$$

$$\bar{\varepsilon} = \frac{2}{\sqrt{3}}\ln\left(\sqrt{1+\gamma^2/4} + \frac{\gamma}{2}\right) + \ln(\frac{h_o}{h}) \quad (7)$$

$$\bar{\varepsilon} = \ln\left(\sqrt{1+\gamma^2}\right) + \ln(\frac{h_o}{h}) \quad (8)$$

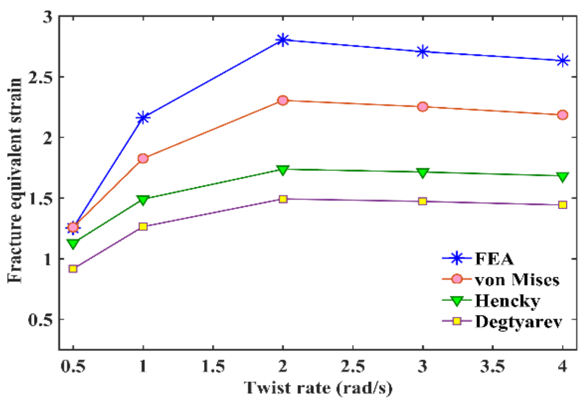

Figure 6 . Comparison of the FEAand the von Mises, modified Hencky, and Dakhtyarov models.

Conclusion

Key findings of this study can be summarized as:

1. Torque required for a given twist angle decreased with increasing twist rate, particularly at larger angles.
2. At a fixed twist angle, log–log plots of torque versus twist rate were linear, with negative slope increasing with twist angle.
3. The twist-rate sensitivity index decreased linearly with twist angle, indicating the dominance of strain-softening mechanisms.
4. The conventional Johnson–Cook model with the Ludwik term poorly matched FEA results, whereas the modified model with exponential terms showed excellent agreement.
5. Von Mises equivalent strain closely matched FEA results, outperforming Hencky and Dakhtyarov predictions; discrepancies increased at higher twist rates.

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