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ULTRASONIC TEMPORARY SOFTENING AND RESIDUAL SOFTENING IN TERMS OF THE SYNTHETIC THEORY

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Abstract

The present paper is aimed to model the effects of the application of ultrasonic such as temporary softening and residual hardening. While temporary softening is noted in the simultaneous action of ultrasound and mechanical forces, residual effects reveal themselves after switching off the ultrasound. The mathematical description of these phenomena is conducted in terms of the synthetic theory of irrecoverable deformation. A good match is obtained between the model and experimental results.

1 Introduction

Many studies related to the effect of ultrasound on the deformation behavior of metals have shown almost similar results for the behavior of these metals under the influence of ultrasound [1,2,3], mentioning briefly (Fig. 1): (i) Temporary softening, where the plastic flow of metals occurs at stresses less than during standard loading range. This phenomenon is referred to as Ultrasound-assisted deformation (acoustoplasticity). (ii) Ultrasonic residual effects. Where vibration can permanently change the mechanical properties of the metals, and it is also called deformation in the post-sonicated period.

Researchers introduced several models to simulate these phenomena; most of them have focused on varying the friction coefficient for reducing the friction forces to explain the application of ultrasonic energy on simulating ultrasonic-assisted deformation processes [4,5,6]. Siddiq [7,8] found that combined acoustic softening (volume) and thermal softening (surface) effects in the material model perform more authentic simulations of ultrasonic consolidation processes. Recent studies show that the implied microstructural deformation can be predicted using developed micromechanics-based constitutive models [9,10].

This work is progress in our research of modeling the effect of ultrasound on the plastic deformation of metals [11,12,13] that started with Rusinko [14] in terms of the synthetic theory of irrecoverable deformation [15]. Here we discuss and model the result obtained by Kang et al. [16], which involves the residual softening for copper in addition to acoustic temporary softening.

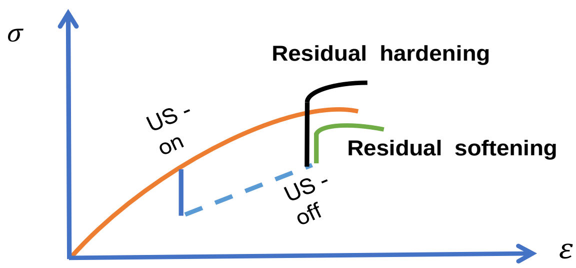

Figure 1. Ultrasonic effects

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2 Synthetic theory

In terms of this theory [12], we can determine the plastic deformation at a point of the body through deformations at the microlevel of material, which means that, as a sum of plastic shifts in active slips systems where the resolved shear stress overpasses the material yield strength.

$$\vec{\boldsymbol{e}} = \iiint\limits_V \varphi_N \overrightarrow{\boldsymbol{N}} dV, \tag{1}$$

where φ_N– plastic strain intensity – is an average measure of plastic deformation within one slip system. The plastic flow rule on the microlevel of material can be defined as

$$r\varphi_N = H_N^2 - S_S^2 \tag{2}$$

We represent the loading by stress vector $\vec{\boldsymbol{S}}\left(\sqrt{2/3}\,\sigma, 0{,}0\right)$ which elongates along the S_1 axis, as a result, the formulae (1) and (2) will take the following form

$$\varphi_N = \frac{2}{3r}\left[(\sigma\sin\beta\cos\lambda)^2 - \sigma_S^2\right], \tag{3}$$

$$e = \frac{4\pi}{3r}\int\limits_{\beta_1}^{\pi/2}\int\limits_0^{\lambda_1}\left[(\sigma\sin\beta\cos\lambda)^2 - \sigma_S^2\right]\sin\beta\cos\lambda\cos\beta\, d\lambda d\beta = a_0\Phi(b), \tag{4}$$

$$a_0 = \frac{\pi\sigma_S^2}{9r_0}, \qquad \Phi(b) = \frac{1}{b^2}\left[2\sqrt{1-b^2} - 5b^2\sqrt{1-b^2} + 3b^4\ln\frac{1+\sqrt{1-b^2}}{b}\right], \tag{5}$$

where r is the model constant determining the slope of $\sigma\sim\varepsilon$ curves $[r] = \mathrm{Mpa}^2$, σ_S is the yield strength of the material.

The integration boundaries in (4) are acquired from (3) by letting $\varphi_N = 0$ and $\lambda = 0$:

$$\sin\beta_1 = \frac{\sigma_S}{\sigma} \equiv b, \quad \cos\lambda_1 = \frac{\sigma_S}{\sigma\sin\beta}. \tag{6}$$

3 Extension of the Synthetic Theory to the case of plastic straining in the presence of ultrasound

To model the effects of ultrasound on the plastic strain of metals, Eq. (2) will be extended by two terms, $U_t$and U_r as:

$$r\varphi_{NU} = H_N^2 + U_t^2 + U_r^2 - S_S^2, \tag{7}$$

where U_t represents the acoustoplasticity (temporary softening) action of ultrasound:

$$U_t = A_1{\sigma_m}^{A_2}(2 - e^{-pt})\left(\vec{\boldsymbol{u}}\cdot\overrightarrow{\boldsymbol{N}}\right), \quad t \in [0, \tau] \tag{8}$$

where σ_m is vibrating stress amplitude Mpa, p and A_k ($k = 1{,}2$) are model constants, τ is the sonication duration and $\vec{\boldsymbol{u}}$ is a unit vector expressing the vibration mode (torsional, longitudinal, etc.). For longitudinal sonication, the vector has $(1{,}0{,}0)$ coordinates in $\mathcal{S}^3$.

The stress amplitude links to the temporary softening effect by the power function $A_1{\sigma_m}^{A_2}$. Consequently, the temporary multiplication of ultrasound-induced defects (ψ_{NU}) is linked to the term $A_1{\sigma_m}^{A_2}(2 - e^{-pt})$[11]. We define U_r as stress and time-dependent function:

$$U_r = h(\varepsilon - \sigma_m) \times A_3\int\limits_0^{\tau}{\sigma_m}^{A_4}dt, \tag{9}$$

where h is the Heaviside step function, ε is any positive insignificantly small number. Therefore, ultrasound of any intensity results in a negative value of $(\varepsilon - U)$. The $h(\varepsilon - U)$ function means that the U_r term comes into effect only after switching off the ultrasound. The intensity of sonication is not the only parameter ruling the magnitude of the hardening effect. Specifically, sonication duration plays an important role; namely, the time-integral in (9) reflects the time-dependent value of ultrasonic energy inserted into the material. Outlining, the post-sonicated-defect-pattern that is leading to the change in material characteristics/response after the acoustoplasticity is reflected by U_r.

$$r\varphi_{NU} = H_N^2 + U_t^2 - U_r^2 - S_S^2. \tag{10}$$

where φ_{NU} is the plastic strain intensity accumulated during the acoustoplasticity.

4 Uniaxial loading coupled with longitudinal vibration

4.1 Once the vibration started, formulae (8) and (10) at $\boldsymbol{t} = \mathbf{0}$ will give

$$\begin{gathered} r\varphi_{NU} = \left(\vec{\boldsymbol{S}} \cdot \vec{\boldsymbol{N}}\right)^2 + \left[A_1 {\sigma_m}^{A_2} \left(\vec{\boldsymbol{u}} \cdot \vec{\boldsymbol{N}}\right)\right]^2 - S_S^2 = \\ = \frac{2}{3}\left[(\sigma_U \sin\beta \cos\lambda)^2 + \frac{3}{2}\left[A_1 {\sigma_m}^{A_2} \sin\beta \cos\lambda\right]^2 - \sigma_S^2\right]. \end{gathered} \tag{11}$$

Where $\varphi_{NU} = 0$, the boundary angles β and λ are:

$$\begin{aligned} \sin\beta_{1U} &= \frac{\sigma_S}{\sqrt{\sigma_U^2 + \frac{3}{2}\left(A_1 {\sigma_m}^{A_2}\right)^2}} \equiv b_U, \\ \cos\lambda_{1U} &= \frac{\sigma_S}{\sqrt{\sigma_U^2 + \frac{3}{2}\left(A_1 {\sigma_m}^{A_2}\right)^2} \sin\beta}. \end{aligned} \tag{12}$$

Equalizing b_U and b from (12) and (6) yields the value of the stress σ_U which keeps the same deformation as before switching on the US:

$$\sigma_U = \sqrt{\sigma^2 - \frac{3}{2}\left(A_1 {\sigma_m}^{A_2}\right)^2}. \tag{13}$$

Eq. (13) calculates the ultrasound-induced stress drop.

4.2 At the time of simultaneous action of unidirectional loading and ultrasound, $\boldsymbol{t} \in [\mathbf{0}, \boldsymbol{\tau}]$, Eq. (10) become

$$\begin{gathered} r\varphi_{NU} = \\ \frac{2}{3}\left[(\sigma_U \sin\beta \cos\lambda)^2 + \frac{3}{2}\left[A_1 U^{A_2}\left(2 - e^{-pt}\right) \sin\beta \cos\lambda\right]^2 - \sigma_S^2\right]. \end{gathered} \tag{14}$$

Plastic deformation in temporary softening (e_U) is calculated by Eq. (1) with the integrand from (14). As a result,

$$e_U = a_0 \Phi(b_U), \qquad b_U = \frac{\sigma_S}{\sqrt{\sigma_U^2 + \frac{3}{2}\left(A_1 {\sigma_m}^{A_2}\left(2 - e^{-pt}\right)\right)^2}}. \tag{15}$$

4.3 After US is off, $\boldsymbol{U_t} = \mathbf{0}$ and $\boldsymbol{U_r} > \mathbf{0}$, the plastic strain intensity becomes of negative sign, i.e., the development of plastic deformation ceases. Eqs. (9) and (10) become

$$H_N^2 = r\varphi_{NU} + \frac{3}{2}[A_3{\sigma_m}^{A_4}\tau]^2 + S_S^2, \tag{16}$$

to plastic strain intensity from remains negative, we have an elastic deformation increment only,

$$r\varphi_{NU} = \frac{2}{3}\left[(\sigma \sin\beta \cos\lambda)^2 + \frac{3}{2}[A_3{\sigma_m}^{A_4}\tau]^2 - \sigma_S^2\right] \tag{17}$$

Comparing formulas (17) and (3), it is clear that $\varphi_{NU} > \varphi_N$ and we obtain the case of ultrasonic residual softening, i.e., the $\sigma \sim \varepsilon$ curve locates beneath that, where unidirectional load acts alone.

5 Results

We plot stress-strain curves using the formulae mentioned in the previous section obtained in terms of the synthetic theory.

Initially, we select the value of r that can match the standard $\sigma \sim \varepsilon$ curve (without ultrasound) to the experimental one. The theoretical $\sigma \sim \varepsilon$ diagram from Fig. 2, which is plotted using Eqs. (4)-(6) at $r = 40000\ \mathrm{MPa}^2$, $E = 2.5\ \mathrm{Gpa}$, and $\sigma_S = 160\ \mathrm{MPa}$, shows good agreement with experimental data.

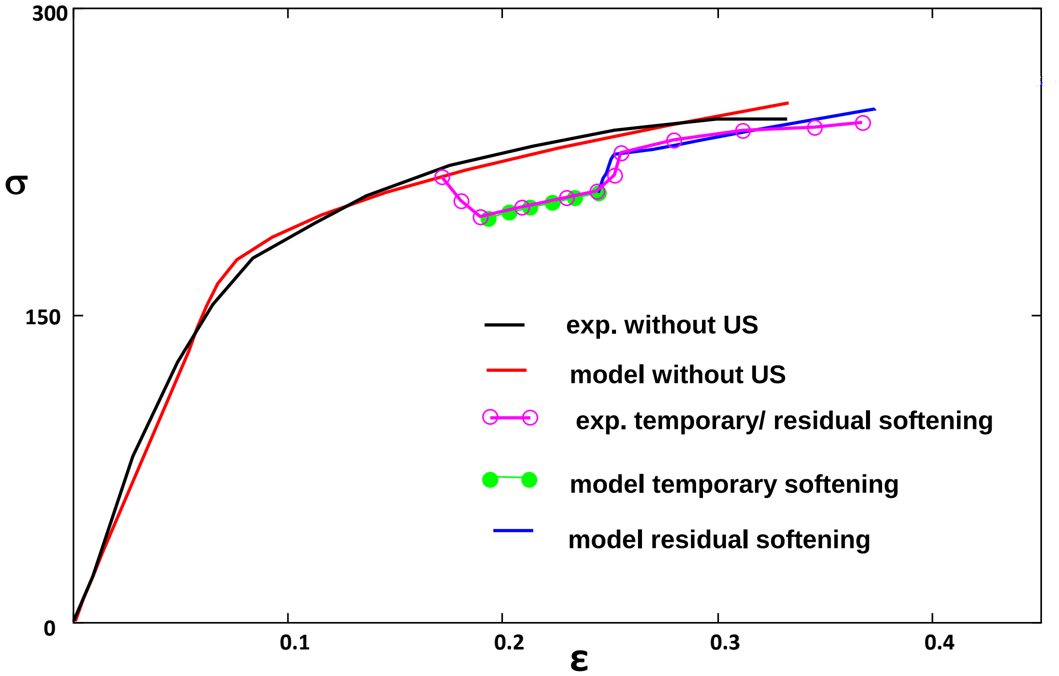

Figure 2. Stress~strain compression diagrams (experimental data [13] with model curves).

Once the stress reaches $218\ \mathrm{MPa}$, ultrasound is on with strain rate increased to $(1/\mathrm{s})$. The value of the amplitude A used in the experiment is $1.3\ \mu\mathrm{m}$ [13]. To calculate the amplitude of oscillating stress representing A, presented in the following formula:

$$\sigma_m = E\frac{2\pi f}{c}A, \tag{18}$$

where c is the speed of sound in copper $c = 4760\ \mathrm{m/s}$, and f is the frequency ($f = 20\ \mathrm{kHz}$) [1]. As a result, $\sigma_m = 4.39\ \mathrm{Mpa}$. Next, we plot $\sigma\sim\varepsilon$ diagrams under the action of ultrasound using formula (15). Constants, $A_1 = 43 \times 10^{-2}\ \mathrm{MPa}^{1-A_2}$, $A_2 = 0.5$, $p = 1 \times 10^{-3}\ s^{-1}$, lead to accurate results.
Finally, to model the deformation of post-sonicated material (residual stress), which is calculated using Eqs. (17) and (1), at $A_3 = 2.1 \times 10^{-7}\ \mathrm{MPa}^{1-A_4}$ and $A_4 = 1.1$ show a good match with experimental data.

6 Conclusion

This study modeled acoustic temporary softening and acoustic residual softening in vibration-assisted plastic deformation. The synthetic theory of irrecoverable deformation was developed to set the model. Good agreement between the analytical results with experimental data was shown. Two terms, which govern the deformation characteristic of material during sonication and after it, were inserted into the plastic flow rule. The first term reflects the accumulation and dynamic annealing of defects, two opposing processes occurring during acoustoplasticity; the dynamic annealing of defects has a dominant role in the temporary softening. The second term describes how post-sonicated material's defect structure manipulates the material's supplementary deformation (also called residual softening or hardening).

References

[1] Gale E. Nevill, J.F.R.B: The effect of vibrations on the static yield strength of a low-carbon steel, ASTM Proc., (1957), 57, pp. 751-758.
[2] Langenecker, 1966, B. Langenecker: Effects of ultrasound on deformation characteristics of metals, IEEE Trans. Sonics Ultrasonics, (1966),13, pp. 1-8.
[3] Z. Yao, G.-Y. Kim, Z. Wang, L. Faidley, Q. Zou, D. Mei, Z. Chen: Acoustic softening and residual hardening in aluminum: modeling and experiments, Int. J. Plast., (2012), 39, pp. 75-87, doi.org/10.1016/j.ijplas.2012.06.003.
[4] Y. Ashida, H. Aoyama: Press forming using ultrasonic vibration, J Mater Process Technol, (2007), 187-1887, pp. 118-122, DOI: 10.1016/j.jmatprotec.2006.11.174.
[5] Yusof Daud, Margaret Lucas, Zhihong Huang: Modelling the effects of superimposed ultrasonic vibrations on tension and compression tests of aluminium, J Mater Process Technol, (2007), 186, pp. 179-190, DOI: 10.1016/j.jmatprotec.2006.12.032.
[6] Mashahiro Hayashi, Masahiko Jin, Sutasn Thipprakmas, Masao Murakawa, Jung-Chung Hung, Yu-Chung Tsai, *et al.*; Simulation of ultrasonic-vibration drawing using the finite element method (fem), J Mater Process Technol, (2003), 140, pp. 30-35, DOI: 10.1016/S0924-0136(03)00699-X
[7] A. Siddiq, E. Ghassemie: Theoretical and fe analysis of ultrasonic welding of aluminum alloy 3003, J Manuf Sci Eng, (2009),131, pp. 041007.1-041007.11, DOI: 10.1115/1.3160583.
[8] A. Siddiq, E. Ghassemieh: Thermomechanical analyses of ultrasonic welding process using thermal and acoustic softening effects, Mech Mater, (2008), 40, pp. 982-1000, DOI: 10.1016/j.mechmat.2008.06.004.
[9] E. Mariani, E. Ghassemieh: Microstructure evolution of 6061 o al alloy during ultrasonic consolidation: an insight from electron backscatter diffraction, Acta Mater, (2010), 58, pp. 2492-2503, DOI: 10.1016/j.actamat.2009.12.035
[10] Z. Zhu, B.P. Wynne, E. Ghassemieh: A. Siddiq, Microstructural analysis of ultrasonic welded aa6061 by electron backscattered diffraction, Rare Met Mater Eng, (2009), 38, pp. 147-151.
[11] Ali H. Alhilfi et al., Modelling of ultrasonic temporary and residual effects, JTAM, Sofia, vol. 52 Issue 1 pp. 064-074 (2022).
[12] Rusinko, A et al., An analytic description of the creep deformation of metals in the ultrasonic field, Mech Time-Depend Mater (2021). https://doi.org/10.1007/s11043-021-09505-0
[13] Rusinko, A et al., The Effect of Ultrasound on Strain-hardened Metals, Acta Polytechnica Hungarica Acta Polytechnica Hungarica, 18, 8, 2021, P221-233, DOI: 10.12700/APH.18.8.2021.8.12
[14] Rusinko, A: Analytical description of ultrasonic hardening and softening, Ultrasonics, 2011, 51, pp. 709–714, DOI: 10.1016/j.ultras.2011.02.003.
[15] Rusinko, A., & Rusinko, K: Plasticity and Creep of Metals, Springer Science & Business Media, 2011.
[16] J. Kang, X. Liu, and M. Xu: Plastic deformation of pure copper in ultrasonic assisted micro-tensile test, Mater. Sci. Eng. A, 2020, vol. 785, p. 139364, DOI: 10.1016/j.msea.2020.139364