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Modeling the effect of multiple pulse treatment on deformation processing

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Abstract. The present study reports the application of multiple pulse treatment (MPT) in order to improve plasticity of metal materials. The mechanism of electropulse influence on metal properties is explained by using the permanent strain and the specific energy as the main parameters in the defining relationship. On the one hand, a high current alters the yield stress of alloys. On the other hand, an assessment of the improved plasticity in MPT case is due to computational solutions of rolling treatment. The results of the article seem to have promising applications in metal treatment.

1. Introduction

In the last years, a great effort has been focused on providing an innovative technique that leads to the improved plasticity and maintained strength of metal alloys. The present study represents the MPT technique causing such alterations. MPT is a process of applying a high current of certain duration to metal specimens being, separately or simultaneously, deformed. Since numerous experiments have been carried out, the electropulse influence is clear. For instance, in MPT case of Titanium alloys, the plasticity is three times greater than usual but there is an 8% decrease in strength.

The MPT-caused increase in plastic properties of metals is named the effect of electroplasticity [1]. Physical hypotheses describing the effect vary from the microscopic "electron wind" concept [2] to the macroscopic high local temperature gradient concept [1]; a high local gradient of temperature field at microstructure-level causes mosaic temperature structure at macro-level and leads to the increased plasticity. That is, the local recrystallization, phase changes, the compressive residual stress due to local heating and defects healing should be the main characteristics causing the increase [1-3].

By means of investigating copper specimens, the present paper firstly reports the effect of MPT technique on the variation of the yield stress. The experiments contain the separate high current pulse and loading actions. Some experimental results are highlighted. Secondly, a basic explanation of the effect of electroplasticity is given. Both, the permanent strain and the specific energy (or the amplitude of current density), are assumed as the main parameters altering the defining relationship. Finally, a simple computational model is provided by use of engineering software DEFORM-2D V9.0. Changing adjusting parameters, the alterations of the plasticity in MPT case of rolling are estimated.

2. Experimental

Similar to some research reports, 99% copper alloys were examined in this paper. The twelve as-received polycrystalline samples were taken. Each had a diameter of 1.64mm and a length of 100mm. They were differently pretreated and then uniaxial tensile tests at room temperature were carried out.

A self-made electropulsing generator discharging positive direction multiple pulses was used to apply a high current to the specimens. The surface maximum temperature of the materials was directly detected by the Raytec® MX2 infrared thermoscope.

2.1. Electropulse treatment of 99% copper alloys

The samples were divided into four groups. Samples I, reference specimens, were stretched to 9% plastic deformation then completely unloaded and finally thermally treated (annealing for 5min, T = 673K). Samples II got MPT only. Samples III were stretched to 11.9% plastic deformation, completely unloaded and MP-treated, accordingly. Samples IV were rolled out to a width of 2.16mm (19.2% plastic deformation) then they got MPT. In these experiments, MPT always contained three short electropulses of 0.12s duration each one. The 50Hz mains frequency was maintained in all the cases (table 1).

After different pretreatments, all the samples were air-cooled and stretched with constant speed of 2mm/min to the beginning of necking.

Table 1. MPT testing conditions of 99% copper alloys.

Sample	Frequency (Hz)	Duration (s)	Pulse Number	j_m [a] (A/mm^2)	Temperature (K)
I	-	-	-	-	673
II	50	0.12	3	663	594
III	50	0.12	3	636	575
IV	50	0.12	3	648	582

[a] j_m means amplitude of current density in MPT case

The waveform of electropulsing was detected in situ by a TDS3012 digital storage oscilloscope and it was a damped oscillation wave (figure 1). Here, the waveforms of different electropulsing were similar, but the values of the amplitude of current density varied for different specimens.

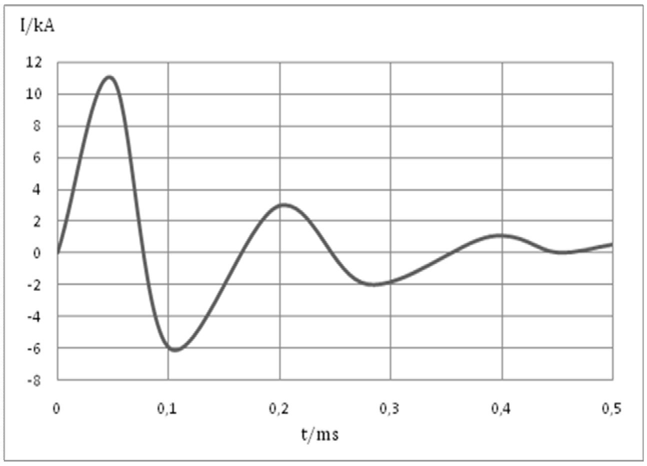

Figure 1. Typical waveform of electropulsing.

2.2. Results

Assuming the sectional area to be unchanged long enough, table 2 was obtained for a single specimen of each group with maximum signs of the effect.

Figure 2 reveals alterations of the yield stress of MP-treated air-cooled samples. Combining with table 1, it can be indicated:

- The yield stress is affected by both electropulsing and permanent strain (plastic strain gained before electropulsing).

Table 2. Yield stress of 99% copper alloys.

Sample №	Sectional area (mm^2)	Load (kg)	Yield stress (kg/ mm^2)
1(I)	2.1	65	30.8
2(II)	2.1	50	23.7
3(III)	1.9	30	15.9
4(IV)	1.8	16	9.0

- The yield stress of MP-treated air-cooled samples decreases. The more permanent strain there is the greater the decrease in the yield stress.
- The temperature during MPT is relatively high (above the recrystallization temperature but less that the melting temperature) similar to a thermal treatment case. However, the comparison of the three MP-treated samples and a purely heated one has shown advantages of MPT. The failure strain of sample №1 was 24% less, on average, than those of in MPT case.
- The decrease in the yield stress for sample №2 can be explained by its hardening features as well as by multiple defects.

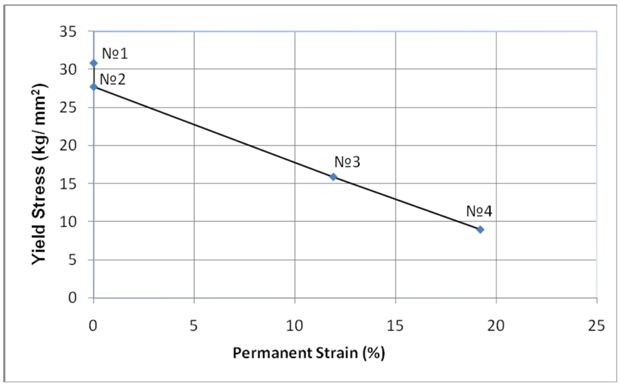

Figure 2. Alterations of the yield stress in MPT case.

3. Discussion

Numerous studies [1, 3-4] have shown that the MPT technique leads to the improved plasticity (the effect of electroplasticity) only since a pulse duration ~ 0.1s and amplitude of current density $\sim 10^9 A/m^2$. Besides, the permanent strain or multiple material defects are vital for the increase and there is no effect without either of these conditions. The basic physical explanation of the increase is the assumption concerning the effect of a high-density current on the occurrence of faults (microcracks and micropores) in the crystalline structure during the process of plastic deformation. Thus, this effect can be explained by the redistribution or concentration of the current and the accompanying temperature field, caused by differences between the physical parameters (conductivity) of the microdefects and those of the bulk of the material, as well as by the boundary geometry of the microdefects. Such a locally nonuniform distribution of physical fields can actually cause macroscopic increases in plasticity, which is observed experimentally [1].

Studies [1, 5-9] have shown that MPT, stimulating the mobility of dislocations, consists of thermal and athermal effects during the applied electropulsing. The thermal effect could be attributed to Joule heating produced by pulsed current. The explanation of the athermal effects claims that the improved plasticity results from mosaic temperature structure at macro-level caused by a high local gradient of temperature field at micro-level [1-3, 10]. In addition, according to [4], a remarkably increased activity of the dislocations implies the electropulsing since dislocation motions are involved in recrystallization.

At the end, a relatively small decrease in the tensile strength of MP-treated metal alloys is remarkable. For instance, in the above-mentioned case of Titanium alloys the decrease is only 8% while the majority of the examined metal materials [2-5] have shown 10% decrease, on average. Thus, for metal materials MPT provides an increase in plasticity as well as rough strength preservation.

3.1. Defining relationship in the case of MPT

Summarizing the experimental data of [1-3] and that of this paper, the defining relationship is obtained since some physical hypotheses are proposed. First, the principle of equidistance: the plastic part of the stress-strain curve moves down along the elastic part without change of shape at all (figure 3). Second, a kinematic parameter of permanent strain and a certain value of specific energy are the principal features of the effect of electroplasticity. Third, the data of tensile tests of the separate electropulsing and deformation cases is generalized in order to derive the defining relationship of the simultaneous electropulsing and deformation actions. In addition, the work of plastic deformation is used as a kinematic parameter as well as the permanent strain.

Since the separate uniaxial tensile tests are of the pattern of loading until the observation of plastic deformation - full unloading - electropulsing - repeated loading - etc, the defining relationship of one-dimensional case is derived as:

$$\bar{\sigma}^* = \bar{\sigma} - \psi(\varepsilon_p) \cdot \chi(q) \tag{1}$$

where $\bar{\sigma}^*$ - a flow stress parameter in MPT case, ε_p - permanent strain, q - specific energy, $\bar{\sigma}$ - a pure flow stress without MPT, $\psi(\varepsilon_p)$ and $\chi(q)$ - experimentally obtained functions. For many-dimensional case of the simultaneous electropulsing-deformation actions, since (1) is used as "a single-step equation" and $\Delta q \to 0$, the defining relationship is in the form of

$$\sigma_i^* = \sigma_i - \int_0^q \psi(\varepsilon_i^{(p)}) \cdot \chi^{'}(q) dq \tag{2}$$

where σ_i^* - effective stress in MPT case, $\varepsilon_i^{(p)}$ - effective plastic strain, q - specific energy ($q \sim \tau \cdot j_m^2$), τ - an electropulse duration, σ_i - effective stress without MPT; the form of functions ψ, χ - might differ from those of above.

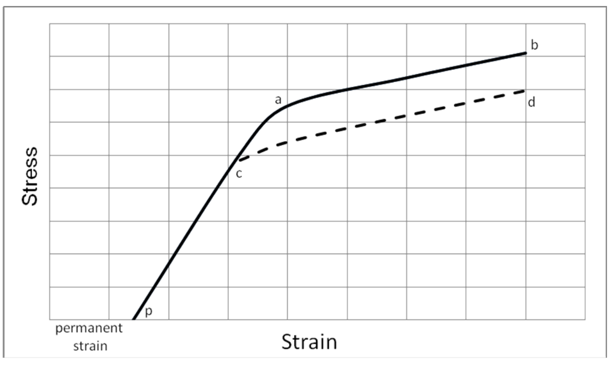

Figure 3. Change of the stress-strain curve in MPT case.

Figure 3: since a pulse applied at point 'p', repeated loading occurs along 'pcd' curve instead of typical 'pab' curve.

An alternative is of a similar origin of (2) but so that the defining relationship for many-dimensional case can be presented in terms of the effective strain

$$\varepsilon_i^* = \varepsilon_i + \int_0^q \frac{\partial f\left(\sigma_i, \psi(\varepsilon_i^{(p)}) \cdot \chi(q)\right)}{\partial(\psi\chi)} \cdot \psi(\varepsilon_i^{(p)}) \cdot \chi'(q) dq \tag{3}$$

It should be mentioned that the equations (2) and (3) are not necessarily equivalent so when it comes to a practical use only one of them is to be adopted as the defining relationship. The difference is mainly because (3) is supposed to depend not only on an effective strain parameter as in the above case but also on a current effective stress.

In addition, using the work of plastic deformation as a kinematic parameter [1], the defining relationship with the same meaning as (1) but in a more complicated form can be derived. In the case of a linear stress-strain curve ($\bar{\sigma} = \sigma_0 + m \cdot \bar{\varepsilon}$)

$$\bar{\sigma}^* = \sigma_0 \cdot \left(1 + \frac{2m}{\sigma_0^2} \cdot \kappa\right)^{1/2} \tag{4}$$

where $\bar{\sigma}^*$ - flow stress in MPT case, σ_0 - the yield stress, m - material constant, κ - a state parameter of structure calculated as

$$d\kappa = \varphi_1(W_p, q) dW_p + \varphi_2(W_p, q) dq \tag{5}$$

where W_p - the work of plastic deformation ($dW_p = \bar{\sigma} \cdot d\varepsilon_p$); the functions $\varphi_1(W_p, q)$, $\varphi_2(W_p, q)$ can be found directly from the experiments since $q = const$, $W_p = const$.

3.2. Damage factor in the case of MPT

Since normalized Cockroft-Latham fracture criterion (damage factor) is used to estimate the plasticity in general, it seems pertinent to use it in the case of MPT as well.

The usual damage factor increases while a material is deformed. The fracture occurs when the damage factor has reached its critical value. The critical value of the damage factor D_{cr} must be determined through physical experimentation. The damage factor D_f is defined by

$$D_f = \int_0^{\varepsilon_i} \frac{\sigma_1}{\sigma_i} d\varepsilon_i \tag{6}$$

where σ_1 - maximum principal stress, σ_i - effective stress, $d\varepsilon_i$ - effective strain increment. The plasticity R_p is calculated through

$$R_p = (1 - \frac{D_f}{D_{cr}}) \cdot 100\% \tag{7}$$

In the case of MPT some transformation of the damage factor concept is done. Namely, assuming that the MPT technique increases D_{cr}, the improved plasticity R_p is assessed by means of equations (2) or (3) since directly calculated via (6) and (7). The increment Δ of D_{cr} in the MPT case can be found as

$$\Delta = \begin{cases} D_{0cr} \cdot \ln\left(\dfrac{a \cdot D_{0cr}}{D_f^*}\right), & if \quad D_f^* > 0 \\ 0, \quad if \quad D_f^* = 0 \end{cases} \tag{8}$$

where D_{0cr} - the critical value of the damage factor of pure materials; D_f^* - the MPT damage factor calculated by (6) since σ_i replaced with σ_i^* or ε_i with ε_i^*: if $\sigma_i = \sigma_1$, the usage of (2) is irrelevant but (3) is pertinent; a - experimentally obtained parameter, since the plasticity in MPT case three times greater than usual, $a = 3$.

At the end, it is remarkable that $\Delta = 0$ at once $D_f^* = 3 \cdot D_{0cr}$ and MPT cannot lead to an increase in plasticity any more. Thus, the application of the Cockroft-Latham fracture criterion in order to assess the increased plasticity in the case of MPT seems to be useful.

4. Computational

Nowadays, there is a rapid development of computer technologies used for analyzing different kinds of metal treatments. Among them is DEFORM, an engineering software that enables designers to analyze metal forming, heat treatment, machining and mechanical joining processes on the computer rather than the shop floor using trial and error. Since DEFORM has proven itself to be extremely effective in a wide range of research and industrial applications, the software is used here to model the MPT rolling and assess the plasticity computationally. Thereby, the simplest 2d-model has been created to analyze the effect of electroplasticity and provide an approach for establishing a suitable MPT technology of rolling.

This rolling model is a 2d plane strain case involving two working rolls (cathode), 50mm diameter and two contact rolls (anode), 30mm diameter. The voltage between cathode and anode is 50V. The test sample ("workpiece") is rigid-plastic and has a length of 100mm, a width of 6mm and electric resistance of 0.0018 Ohm-mm. The distance between the centers of the working and contact rolls is 60 mm (figure 4). The angular velocity of the working rolls of 15rad/s is relatively high so it imitates a pulse treatment since constant voltage. In other words, the valid cathode-anode contact, i.e. the direct current duration, of 0.3s is short enough to be considered a pulse treatment for steady flow of duration 0.12s.

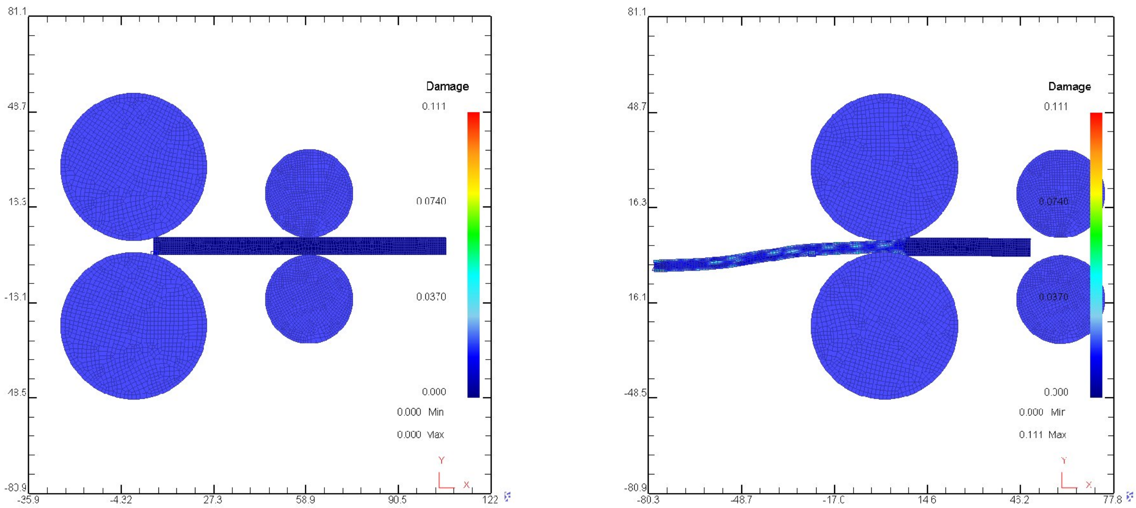

Figure 4. Image of MPT in rolling case.

Some nodes in the mesh have permanent strain before the rolling starts in order to imitate structural nonuniformity. Elastic deformations are neglected. Moreover, focusing on athermal meaning of the effect and taking into account that the duration of energy dissipation [1] in MPT case is considerably

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less than that of heat transfer, the thermal influence on plasticity is neglected; in a real process the influence of thermal strain can be neglected since intensive cooling of samples during MPT.

Using appropriate equations set [1], since (2) is the defining relationship, the programming algorithm can be presented as

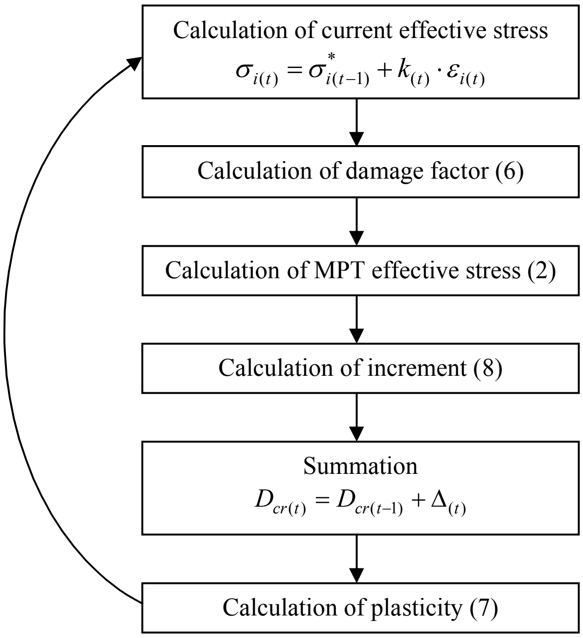

Figure 4. Principle scheme of numerical calculation.

Here, t=1, 2, 3,...- iteration steps, k - approximating parameter, $\sigma^*_{i(0)} = 0$. Since $\Delta_n = 0$, where n is the last iteration step, the calculation ends because of "the failure of material". The damage factor and rest parameters are specified at each element. In addition, such mechanical parameters as stress, strain, strain rate, etc can be easily obtained from solution data if necessary.

Assuming critical value of the damage factor $D_{0cr} = 0.2$, the single passing plasticity R_p (from 6 to 4mm) in the MPT case of rolling was 82.5%. In comparison, using a typical defining relationship $\bar{\sigma} = \bar{\sigma}(\bar{\varepsilon};\bar{\varepsilon}';T)$ for Joule (resistance) heating case of rolling, where T - is joule temperature, the single passing plasticity was 44.5%.

5. Conclusion

The effect of electroplasticity, resulting from multiple pulse treatment, is a process of applying a high current of certain duration to metal specimens that leads to an increase in plasticity.

From the experimental data of the MP-treated copper specimens, it should be clear that: the reduction in the yield stress is affected by both electropulses and permanent strain; even though the temperature during the tests is above that of recrystallization, the MPT technique has its advantages against a thermal treatment case in terms of a better-improved plasticity. The failure strain of sample №1(I) was 24% less, on average, than those of in MPT cases.

The effect of electroplasticity can be explained by the redistribution or concentration of the current and the accompanying temperature field, caused by differences between the physical parameters of the microdefects and those of the bulk of the material, as well as by the boundary geometry of the microdefects. The permanent strain or multiple material defects as well as a certain value of specific energy are vital for the increase and there is no effect without either of these conditions. Since some physical hypotheses explaining the effect are proposed, using permanent strain as a kinematic parameter, the defining relationship can be adopted in a form of (2). The increase in plasticity in the case of MPT should be calculated by combination of equations (6-8).

According to the data of numerical solution of a single passing rolling, the plasticity (7) of 82.5% in the case of MPT considerably exceeds that of 44.5% in a resistance heating case of rolling. Thus, MPT should have its advantages against not only thermal treatment but also a resistance heating case of rolling what is probably very useful, especially for hardly-deformed metal materials.

In the end, the MPT technique seems to have promising applications in particular case of rolling as well as in general case of metal treatment.

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