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INFLUENCE OF THE CYCLICAL MECHANIC-THERMAL PROCESSING ON THE STRAIN HARDENING IN THE SURFACE LAYERS OF STEEL PARTS.

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Abstract. *Nowadays, one of the most important problems in the face of academia and engineering is to upgrade the parts' reliability and their life period. Among the used techniques for achieving this aim, highlights the fact of guaranteeing the required quality indicators in their surface layers (a given surface roughness magnitude; the appropriated level, degree and penetration depth of strain hardening; and the appropriated level, sign and penetration depth of the residual stresses). Substantially on these factors dependent the fatigue strength, the wear resistance and the corrosion stability of machine parts. That is why the objective of this study was to investigate the influence of the two and three cyclic mechanic-thermal processing on the strain hardening in the surface layers of the AISI 1045 steel parts. In this sense, various experiments are carried out, using the full factorial experiment for five factors (amount of cycles, cold forming degree, force, temperature and time) at 2-level. As results were obtained both strain hardening exponential models through its degree and penetration depth dependencies on the main cold plastic deformation and ageing parameters. In all the experiments the surface roughness were improved till* R_a*=0.32… 0.16 micrometers.*

Keywords: *cyclical, mechanic-thermal, processing, strain, hardening.*

1. INTRODUCTION

The cyclical mechanic-thermal processing is a kind of substructural hardening that consists of undergoing the parts to several combined cycles of cold plastic deformation and ageing, for obtaining high quality indicators in their surface layers (Gordienko, 1973). This blend: the strain hardening with a dislocation cell nanostructure formation and the ageing for achieving the stability of that highly energetic state till temperatures close to recrystallization temperature, improves the mechanical properties and the performance in the metals and their alloys, particularly in those with the body-centered cubic crystal structure, as the AISI 1045 plain mid-carbon steel, study object in the present research work.

The strain hardening is the effect of the plastic deformation process within the surface layers of the metals and their alloys, which in its turn is associated to the presence of dislocations during such process, that is, the reason for strain hardening is the increase of dislocation density with plastic deformation. The average distance between dislocations decreases and dislocations start blocking the motion of each other, and these phenomena become the metal harder and stronger (Gordienko, 1973; Alfonso, 1990). The role of the combination of cold work and subsequent ageing is also explained by Panwar *et.al* (2007), through analysis of a microalloyed Cu-bearing HSLA (High-Strength Low Alloy) steel; the mechanical properties had been studied at various stages of ageing with and without prior cold work at different percent.

By the most of the researchers it is accepted to clarify the strain hardening through models of observed true stress-true strain curves in the work hardening region after the specimens' tensile tests (M'Guil *et al*., 2011; Wang *et al*., 2012). Before their testing, the specimens are almost always prepared under different cold-forming degrees by means of rolling, burnishing, ultrasonic vibration (Wang *et al*., 2012; Malleswara *et al*., 2011; Vivekananda, 2012), among other methods of surface plastic deformation (Marulanda *et al*., 2014).

There are many ways to model strain hardening, each one of them has its own advantages and disadvantages. The strain hardening can be obtained through statistical dislocation density models, dislocation dynamics model and empirical models (Prassad, 2007).

2. EXPERIMENTAL MATERIALS AND PROCEDURES

2.1 The study object material and its properties in supply state

After a rigorous bibliographical analysis, keeping in mind the kind of processing to achieve (Gordienko, 1973) and the industry reality (ASTM A 29/A 29M – 04), it were evaluated several grades of plain and low-alloy mid-carbon steels, and it was chosen AISI 1045 steel, for being the most economic grade, that allow carry out the objective of the present work.

Starting from a sample, taken in the bar employed to prepare the specimens, was obtained the chemical composition, in %, of studied steel is as follows: C= 0.47, Mn=0.70, Si=0.21, P=0.04, S=0.03, Cr=0.15 and Ni=0.09.

Besides, were determined the following mechanical properties of materials in supply state: the average hardness, HBS 185 (ASTM E 10 – 01a); the yield strength, σ_y =338 MPa; and the tensile (ultimate) strength, σ_u = 620 MPa. The tensile specimens were prepared, according to ASTM E 8M – 04. It was tested three replicas.

The specimens for the cyclical mechanic-thermal processing application, and later on the microhardness test and microstructural test, were machined to little thick-walled cylinders of 30 mm outer diameter, 20 mm inner diameter and 15 mm wide.

2.2 Machines, devices, tools and instruments

The macrohardness measuring of the material in supply state was done using the HB-3000B Manual Digital Display Brinell Hardness Tester/Metal Brinell Durometer.

For the tensile test was used the INSTRON 8500 Universal Tensile Testing Machine (capacity: ~ 226 kN).

The specimens were cut in the STRUERS Labotom-5 Machine, later on they were carried out to the preliminary sizes and undergo to the burnishing into the different cycles of the mechanic-thermal processing in the CY-6140 Universal Gap Bed Lathe (spindle speed: 9… 1600 r/min; max. output torque of spindle: 1500 Nm; range of longitudinal feed: 0.028… 6.43 mm/r; main motor power: 7.5kW). During the burnishing process, all specimens were deformed, applying the follow rate: spindle speed (v) =90m/min and longitudinal feed (f) =0.10mm/r.

The ageing in each cycle had been made in the GALLE KAMP Muffle Electric Oven (maximum power: 1.5 kW).

The surface roughness was evaluated using the comparison method; by means of the ZUZI model 173/2.

Metallographic Microscope and a Conventional Machining Surface Roughness Comparator.

Mounted specimens for the microhardness measurement, and further on the metallographic research, they were ground in STRUERS Labopol-21 Machine, and lastly they were polished in the STRUERS Labopol-5 Machine.

The microhardness measurement had been developed in the metallographic microscope model SCHENK TREBEL, with a Vickers diamond pyramid indenter and its own devices for fixing the specimens.

The metallographic research was carried out using a Metallographic Microscope model OMAX, coupled to a TOSHIBA laptop (5i), and the microstructural observation has been recorded through the OMAX A3590U camera, integrated to mentioned microscope.

A cutting disk for the STRUERS Labopol-5 Machine was used.

Both single point-brazed cutting tools P10 and P20 (ISO R513-1975E) for the preliminary specimens sizing had been used.

For the drilling operation was employed a 60 degree center drilling bit; both M2 drill rods (10 and 18 mm diameter); and a M2 reamer (20 H8 diameter).

The burnishing operation was made using a Yamasa Sx8-1.2 single roll type roller burnishing tool.

A set of carborundum (SiC) emery paper (240, 320 and 600, according to ASTM E 3 – 01) was employed for the specimens grinding, while for the polishing operations one used both diamond paste in sizes 6 μm and 1 μm.

The specimens were etched, using 2% nital (2% HNO_3 and 98% ethanol).

2.3. Design and run of experiments

Cyclical Mechanic-Thermal Processing (CMTP) experiments were carried out on external surfaces of little thick-walled cylinders. In the experiments, the work pieces were burnished after turning on lathe, in the same set-up. While burnishing, the roller burnishing tool is fixed in its own coupled- dynamometer. That dynamometer is capable of measuring three force components. The z- component was taken as the burnishing force.

After each stage of burnishing the specimens have been subjected to the ageing for completing each cycle, that is, it is in order to organize the dislocation, forming sub-grains and sub-borders in all grains by means of cell fragmentation (Gordienko, 1973).

Independently of the applied parameters' combination, due to design of experiments, in all the cases, the surface roughness were improved till R_a=0.32… 0.16 micrometers after burnishing process and remains at the same level after ageing stage, inasmuch the temperature never raised higher than 200º C, therefore it did not form any oxide husk over the surface layer.

In order to reveal a clear picture of cyclical mechanic-thermal processing (CMTP), a series of experiments were conducted on prepared specimens from selected AISI 1045 plain carbon steel, which find a wide range of industrial applications. To that end a full factorial orthogonal array is chosen. The full factorial experiment for five factors at two-level required 32 (2^5) experiments ("Tab.1").

Table 1. Factors and levels chosen for experimentation (common for both degree and penetration depth of strain hardening experiments).

Factors	Low level (-1)	High level (1)
Amount of cycles (K)	2	3
Cold-forming degree (λ), %	4	7
Force (F), kN	0.8	1.5
Temperature (t), ºC	100	200
Time (τ), h	1.0	1.5

3. RESULTS AND DISCUSSION

In cold processing ductile alloys, as AISI 1045 steel in supply state, the strain hardening behavior, the degree and depth of strain hardening were reported mainly as result of plastic deformation, using different models and theory for its foundation (González *et al*., 2010; Kandavel *et al*., 2009; Wu *et al*., 2009).

"Figure 1" shows the in-depth evolution of microhardness profile along the cyclic mechanic-thermal processed surface layers, from their outer bound of strengthened zone till transition zone, with prediction bounds (Pred bnds) of 95 %. For the shown case and for the others, analyzed during the present research work, the microhardness "H", decreases continuously from the outer surface (here it is achieved its maximal value "$H_{\mu max.}$") to the interior of material till its basic microhardness value "$H_{\mu o}$", further this value remains practically constant. In the "Fig. 1" the microhardness is given in Megapascal ("MPa"), and the penetration depth of strain hardening ("DepthSH") is given in millimeters ("mm").

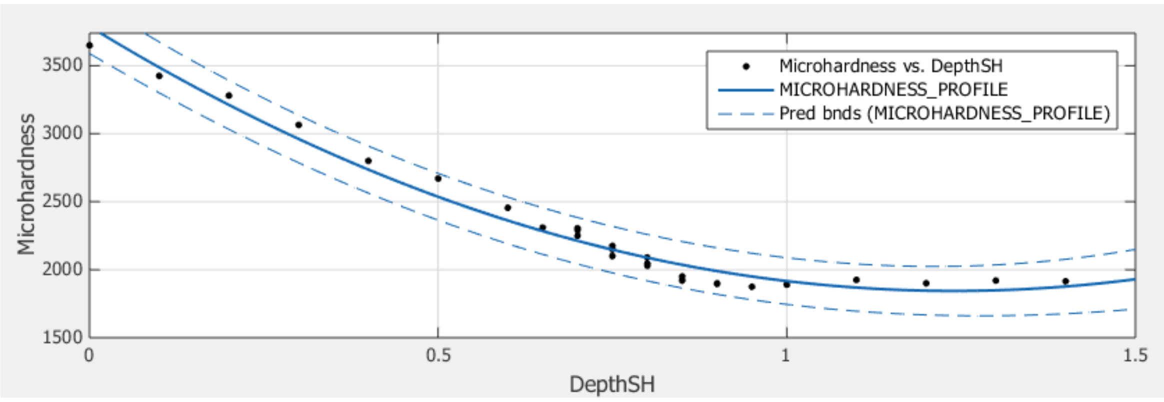

Figure 1. Microhardness profile of AISI 1045 plain carbon steel after three cycles of mechanic-thermal processing

"$H_{\mu max.}$" characterizes the achieved level of strain hardening, and it, as well as "$H_{\mu o}$" is considered as the fundamental parameters for determining the degree and penetration depth magnitudes of strain hardening in the surface layers of machine parts, through the following classic formulas:

$$N = [(H_{\mu max.} - H_{\mu o}) / H_{\mu o}]*100\% \quad (1)$$

$$DepthSH = h = H_{\mu max.} - H_{\mu o} \quad (2)$$

The empirical models are quite a bit used, and they describe the flow stress in terms of power laws as a function of strain with many empirical constants. One of the simple approaches is the Holloman equation which describes the flow stress as a simple power law in strain, is applied several recent works (Wang *et al*., 2012; Prasad, 2007; Chen and Deng, 2011); even in these works had been compared the true stress-strain curve and its polynomial fit curve of a cold rolled low-carbon steel. The Holloman equation is given as

$$\sigma=K\varepsilon^{n_H} \quad (3)$$

Where: σ is the true stress, K is the coefficient of deformation strengthening, ε is the true strain and n_H is the index of strain hardening.

In the present work had been used an empirical model, that evaluates the strain hardening, as the main physical-mechanical quality indicator in the surface layers of the AISI 1045 plain mid-carbon steel. Here were analyzed both degree and penetration depth dependencies of the strain hardening on the main cold plastic deformation and ageing parameters, after specimen having undergone the cyclical mechanic-thermal processing.

"Table 2" shows the experimental matrix and results, for both parameters of strain hardening: degree (N) and penetration depth (h).

Table 2. Experimental matrix and results for degree and penetration depth of strain hardening.

Number of Experiment	Factors					Experimental Results	
	K	λ, %	F, kN	t, ºC	τ, hour	N, %	h, mm
1	3	7	1.5	200	1.5	48.000	0.850
2	2	7	1.5	200	1.5	70.000	0.500
3	3	4	1.5	200	1.5	34.000	0.750
4	2	4	1.5	200	1.5	53.000	0.450
5	3	7	0.8	200	1.5	44.000	0.800
6	2	7	0.8	200	1.5	65.000	0.450
7	3	4	0.8	200	1.5	33.000	0.700
8	2	4	0.8	200	1.5	52.000	0.400
9	3	7	1.5	100	1.5	55.000	0.800
10	2	7	1.5	100	1.5	72.000	0.500
11	3	4	1.5	100	1.5	39.000	0.650
12	2	4	1.5	100	1.5	58.500	0.400
13	3	7	0.8	100	1.5	46.000	0.750
14	2	7	0.8	100	1.5	67.000	0.400
15	3	4	0.8	100	1.5	36.000	0.600
16	2	4	0.8	100	1.5	58.000	0.350
17	3	7	1.5	200	1.0	52.000	0.850
18	2	7	1.5	200	1.0	75.000	0.500
19	3	4	1.5	200	1.0	36.500	0.650
20	2	4	1.5	200	1.0	55.000	0.400
21	3	7	0.8	200	1.0	47.000	0.700
22	2	7	0.8	200	1.0	68.000	0.400
23	3	4	0.8	200	1.0	33.000	0.600
24	2	4	0.8	200	1.0	56.000	0.350
25	3	7	1.5	100	1.0	53.500	0.750
26	2	7	1.5	100	1.0	78.000	0.450
27	3	4	1.5	100	1.0	44.500	0.600
28	2	4	1.5	100	1.0	59.000	0.400
29	3	7	0.8	100	1.0	52.000	0.700
30	2	7	0.8	100	1.0	75.000	0.450
31	3	4	0.8	100	1.0	40.000	0.550
32	2	4	0.8	100	1.0	52.500	0.300

As results of this study were found empirical relationships between the input and output parameters directly by using experimental results, since analytical solutions are difficult to formulate, and the solutions might take time. Especially degree and penetration depth of strain hardening values had been experimented for the main conditions of the cyclical mechanic-thermal processing, then empirical equations were found out using the result of these experiments with the input parameters being in combination the amount of cycles, cold forming degree, force, temperature and time.

This study is not based on analytical realizations, but it provides a good knowledge about the possible outcomes of looking like other processing conditions with similar kind of steel pieces.

Since 60' years of the last century, the researchers had begun to fit different types of statistical models in the engineering field, almost always they at first try with linear fitting, polynomial fittings of various degrees and exponential.

The exponential relevant models for degree and penetration depth of strain hardening with their main statistical characteristics are given, as follows:

$$N=99.335K^{-0.950}\lambda^{0.488}F^{0.112}t^{0.120}\tau^{0.135} \quad (4)$$

Table 3. The fitting results of degree of strain hardening

Intercept	Estimate coefficients	SE	tStat	pValue
	3.82780	0.22116	17.308	8.6602e-16
K	-0.9504	0.03965	-23.97	2.9705e-19
λ	0.48794	0.028728	16.985	1.3603e-15
F	0.11157	0.025575	4.3625	0.00018073
t	-0.12030	0.023194	-5.1866	2.0548e-05
τ	-0.13506	0.039650	-3.4062	0.0021509
Number of observations: 32, Error degrees of freedom: 26 Root Mean Squared Error: 0.0455 R-squared: 0.973, Adjusted R-Squared 0.967 F-statistic vs. constant model: 184, p-value = 1.97e-19				

"Equation (4)" shows that regarding the main effects, the greatest influence on the component "N" is exhibited by the amount of cycles, followed by cold-forming degree, temperature, force and time, correspondingly. At the same time one can analyze that the increment in amount of cycles, temperature and time, reduces the degree of strain hardening, meanwhile cold forming degree and force increase it. In the case of amount of cycles, this fact is because of the difference between the added by the cycle maximal microhardness "$H_{\mu c}$", in the outer bound of strengthened zone of surface layer, and the microhardness in its transition zone "$H_{\mu 0}$", decreases, as much one increases the amount of cycles, so resistance to deformation of steel is followed augment; with the rising of temperature and time, in the surface layer decreases the force factor influence over the thermal factor, which in turn favors the recovering process, that is the microhardness fall. Both, cold-forming degree and force, substantially contribute to increase dislocation density during the cold deformation, that which can be explained through the movement of a large number of dislocations along the gliding planes, their multiplication, and retention into each grain, creating a highly energetic state, that after ageing rearranges the retained dislocations in the grain, forming a dislocation cell substructure, that rise the performance of machine parts, subjected to cyclical mechanic-thermal processing (Gordienko, 1973; Alfonso, 1990).

$$h=0.053K^{1.291}\lambda^{0.339}F^{0.192}t^{0.110}\tau^{0.191} \quad (5)$$

Table 4. The fitting results of penetration depth of strain hardening

Intercept	Estimate coefficients	SE	tStat	pValue
	-2.94330	0.146320	-20.116	2.2596e-17
K	1.29150	0.044656	28.921	2.6709e-21
λ	0.33907	0.032355	10.479	7.9243e-11
F	0.19175	0.028804	6.6571	4.6208e-07
t	0.11050	0.026122	4.2300	0.00025604
τ	0.19148	0.044656	4.2878	0.00021998
Number of observations: 32, Error degrees of freedom: 26 Root Mean Squared Error: 0.0512 R-squared: 0.975, Adjusted R-Squared 0.971 F-statistic vs. constant model: 205, p-value = 4.96e-20				

"Equation (5)" shows that regarding the main effects, the greatest influence on the component "h" is exhibited by the amount of cycles, followed by cold-forming degree, force, temperature and time, correspondingly. All these factors positively influence on the penetration depth of strain hardening, due to in presence of a good refrigerating agent, these parameters guarantee that the strain hardening effect so that it is greater than the thermal softening effect along the surface layer during the plastic deformation process, which is the reason of high penetration depth values of strain hardening obtained in this research work.

4. CONCLUSIONS

Once finished this research, the following are the main conclusions achieved during its development.

- The cyclical mechanic-thermal processing increases, strengthens and stabilizes the strain hardening in the surface layers of steel parts at raising their main physic-mechanic quality indicators.

- As result of high density of retained dislocations into the grains and their rearrangement, forming the sub-borders and subgrains, whithin these last almost not dislocation, each subgrain behaves itself as “pure metal” (Gordienko, 1973).
- There are many empirical models for steel machining, cold and heat forming, several surface treatments, but the cyclical mechanic-thermal processing of steel are not investigated necessarily through empirical models. Empirical models can be utilized in order to have a sense in how CMTP parameters influence on the main characteristics of the strain hardening, although they would not be sufficient to emphasize the physical meaning of the processes.

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