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MODELING AND SIMULATION OF CYCLICAL MECHANIC-THERMAL PROCESSING BY MEANS OF THE FINITE ELEMENT ANALYSIS (FEA).

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Abstract. *The compressive residual stresses formation and strain hardening into the surface layers of machines parts increase their performance, thereby are used a wide variety of surface hardening techniques as rolling and shot peening, but the high obtained levels of these physic-mechanical properties are not stable and fast decrease with the temperature raising during their work. However, at combining the cold plastic deformation with the ageing in two or three cycles, then it is possible increase that stability up to temperatures nearby the metal recrystallization temperature, such kind of treatment is named cyclical mechanic-thermal processing, which modeling and simulation, through the Finite Element Analysis, constitutes the main objective of the present work. In order to fulfill the established objective was employed the FEA-package ANSYS version 14.0, specifically a coupled-field analysis for combining the structural analysis (the plastic deformation of a little and fine plate) with the thermal analysis (the heating and cooling of the plate during the ageing), due to the input of one field analysis depends on the results from another analysis. Model predictions correlate well with experimental results, since with the increase in strain hardening the resistance to deformation of a material is increased and the compressive residual stresses become more compressive.*

Keywords: *FEA, mechanic-thermal, processing, strain, stresses.*

1. INTRODUCTION

The cyclical mechanic-thermal processing (CMTP) of machine parts is an iterative substructural hardening process, in two-five cycles of superficial plastic strain at room temperature, combined with artificial ageing. Such combination is used for creating a stable and consistent energetic state within the surface layers, because of the dislocation cell formation in their nanostructure. In turn, it causes an increase of strain hardening, compressive residual stresses and other properties, as well as in the performance of machine parts (Gordienko, 1973).

The CMTP principle is to apply the dislocation hardening, instead the hardening due phase transformation (like in the classical quenching plus tempering or in thermomechanical processing). Thereby, the governing parameters of the process are the amount of cycles, the cold-forming degree, the applied pressure over the processed part, the ageing temperature and its time. A good selection and combination of these parameters leads to increase of strain hardening and beneficial compressive residual stresses for machine parts submitted to heavy working conditions.

This processing is not widely studied in the literature; just among Russian Scientists it has a wide diffusion since 1960's years, when for the first time Oding *et al*. (1961) published on mechanic-thermal processing through the combination of strain hardening at room temperature with the polygonization annealing for bcc steels; further Ivanova and Gordienko (1964) extended this process to fcc steels; Oding *et al*. (1969) presented the goodness of the mechanic-thermal processing for increasing the heat resistant capabilities, and Gordienko (1973), for the first time obtained the cell substructure in bcc steels by means of the cyclical mechanic-thermal processing. At the present time, there it continues many research works, thus, Savchenkov and Aytkulov (2005) obtained a mix cell- polygonal substructure that increases the corrosion resistant of steel; and finally, Delgado (2014), in her Ph.D. thesis substantiated the her results through the substructural hardening . All these works, including the last two, are purely experimental researches.

Today, numerical simulation plays an indispensable role in the manufacturing process, speeding product design time, while improving quality and performance. Recently, analysts, designer and researchers have begun to use numerical simulation alone as an acceptable means of validation. In many disciplines, including mechanical engineering, virtual prototyping, employing numerical simulation tools based on finite element methods, has replaced traditional break prototyping.

Already, by means of finite elements methods, one can find good results, during the modeling, simulation and analysis of metal cutting (Kukala and Sahoo, 2013; Vishwakarma *et al*., 2011), burnishing (Zemčík *et al*., 2013), shot peening (Bagherifarda and Guagliano, 2011) and other processes of surface cold plastic deformation of metal and their alloys (Szabracki *et al*., 2012; MacDonald and Kulatunga, 2013). But the authors of the present work did not find anything close to numerical modeling and simulation of mechanic-thermal processing through finite element analysis that is why here is presented an attempt for beginning to fill that lack.

2. PROCEDURES OF FINITE ELEMENT ANALYSIS.

The master idea to build a finite element model is to find a configuration that is sufficiently representative to give back phenomena that occur during the modeled process. This idea seems too simple, but sometime it results difficult to execute correctly, like in the case of cyclical mechanic-thermal processing, due to it is necessary to couple all the components of the process, that is to say, the results of each stage constitutes the input of follow stage. Besides, it should keep in mind the material nonlinear behavior and it experiments very strong strain gradients in very small layer during the plastic strain, as well as substructural changes after each stage and each cycle.

To better understand this complex mechanism in the surface layer of pressured and artificially aged material, the modeling and simulation by means of finite element analysis is proposed. After analyzing several FEM programs, ANSYS program was considered the most suitable, because of the possibility to apply the couple-field analysis. A coupled-field analysis is a combination of analyses from different engineering disciplines (physics fields) that interact to solve a global engineering problem; hence, we often refer to a coupled-field analysis as a multiphysics analysis. When the input of one field analysis depends on the results from another analysis, the analyses are coupled.

In ANSYS help like coupled-field analysis the following two distinct methods can be identified: *direct* and *load transfer* (APDL, 2011).

The *direct method* usually involves just one analysis that uses a coupled-field element type containing all necessary degrees of freedom. Coupling is handled by calculating element matrices or element load vectors that contain all necessary terms. The *load transfer methods* involve two or more analyses, each belonging to a different field. One can couple the two fields by applying results from one analysis as loads in another analysis. With a physics file-based load transfer, it must explicitly transfer loads using the physics environment.

The physics analysis is based on a single finite element mesh across physics. It creates physics files that define the physics environment; these files configure the database and prepare the single mesh for a given physics simulation. The general process is to read in the first physics file and solve. Then read in the next physics field, specify the loads to be transferred, and solve the second physics. Use the LDREAD command to link the different physics environments and apply the specified results data from the first physics environment as loads for the next environment's solution across a node-node similar mesh interface, that is why in the present work is used this kind of analysis.

“Figure 1” (APDL, 2011) depicts the data flow for a load transfer coupled physics analysis using multiple physic environments.

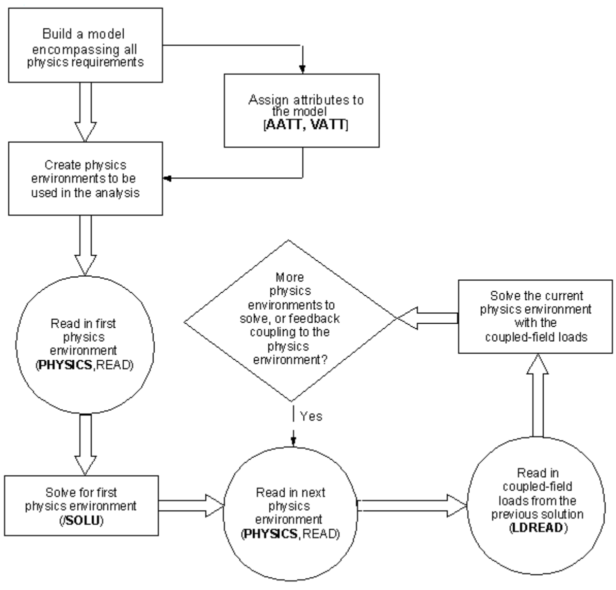

Figure 1(APDL, 2011). Data flow for a load transfer coupled physics analysis using multiple physic environments.

AATT: Associates element attributes with the selected, unmeshed areas.
VATT: Associates element attributes with the selected, unmeshed volumes.
For performing this analysis had been used ANSYS command prompt

2.1 Element Type

In order to develop the coupled field analysis it was selected SOLID186 element, which is a higher order 3-D 20-node solid element that exhibits quadratic displacement behavior. The element is defined by 20 nodes having three degrees of freedom per node: translations in the nodal x, y, and z directions. The element supports plasticity, hyperelasticity, creep, stress stiffening, large deflection, and large strain capabilities. It also has mixed formulation capability for simulating deformations of nearly incompressible elastoplastic materials, and fully incompressible hyperelastic materials.

2.2 Material characterization and its modeling

The success of FEA mostly depends on providing robust modeling of the material. Elastic properties as well as plastic properties should be identified. The goal of this paper being to show 3D FE simulation feasibility, efficient procedure has been privileged in this field. Indeed, the material modeling could have been very sophisticated due to the heterogeneities that are usually observable at different level of cold-formed steel. These heterogeneities are generated by the elaboration process of the plate and after by machining that induces strong structure changes in a thin surface layer. Strain path applied by the press-die is also very complex. The possibilities for material modeling are wide and could include the material heterogeneity, the complex path, the strain rate sensibility, and so on. In this situation, it is not usually proven that complex modeling will provide real improvement on the quality of results, therefore only a few aspects that are considered as essential for this study are retained. The material is considered to be kinematic, not sensible to strain rate in the range of those imposed by the process and mean behavior is considered due to pressing process on the material larger than the affected zone by machining. As pressing imposes mainly large compressive strains on the material, the choice of a global compressive test has been made to carry out the identification of the plastic model.

The object study material is AISI 1045 steel; and its model for cyclical mechanic-thermal processing fits to the category of nonlinear elastic-plastic material with kinematic hardening plasticity (von Mises yield criteria coupled with a kinematic work hardening assumption-bilinear). This model is available in the library module of ANSYS, and for its use had been assigned the following main magnitudes: elastic modulus $E = 2.10^5$ MPa, Poisson's ratio $\nu = 0.3$, yield stress $\sigma_y = 338$ MPa, average tangential modulus $E_t = 2275$ MPa, coefficient of thermal expansion $\alpha = 1.08 \times 10^{-5}\ K^{-1}$.

2.3. Geometry and meshing

The specimen is a fine plate, which dimension are length "l = 25 mm", width "w = 25 mm" and thickness "t = 5 mm". In order to have a practical number of elements for calculations, only the plate was meshed, the pressing tool was considered like a rigid surface and it is represented by the applied pressure. In this modeling process had been used the mapped meshing with hexahedral elements.

2.4. Boundary conditions

Due to its geometrical configuration, the modeled specimen has six flat surfaces: four side relatively narrow surfaces, and two wide main surfaces. The four narrow specimen side surfaces were considered free. Through the top specimen main surface acts the normal pressure, thereby to its bottom main surface was restricted all degree of freedom, to guarantee that model is closed to real condition during laboratory tests.

3. RESULTS AND DISCUSSION

Since long time ago (Gordienko, 1973), it is shown that the best variants of applying the cyclical mechanic-thermal processing (CMTP) are during two or three cycles, because of at only one cycle the amount of retained dislocation is not enough to achieve the necessary level and penetration depth of strain hardening and compressive residual stress in the surface layers of steel parts. At submitting the steel parts to four or more cycles the dislocation density "ρ" can sharply increase its magnitude (over $10^{11}\ m^{-2}$), then the surface layer become brittle like the glass; for this reason in the present study it is take in account the analysis of two and three cycles of CMTP.

Results of the analysis were obtained by using ANSYS time history postprocessor /POST26. This postprocessor is built in the software and used for different functions. History postprocessor/POST26 was used to provide results over the time history and very useful in obtaining accurate results at applying load transfer methods during coupled field analysis.

"Figure 2" depicts simulation of the average of normal residual stress distribution along y-axis direction "SY" in the surface layers during the second cycle of CMTP, while the "Fig. 3" depicts simulation of the average for the third cycle of CMTP. At comparing both stresses distribution one can appraise that the used process of modeling and simulation close to experimental results (Gordienko, 1973; Larikov and Tijonov, 1985), and reflects the influence that exert, on the residual stresses magnitude, the amount of cycles, the cold- forming degree (four percent in the second cycle of the CMTP, while in the third cycle its value raised up to seven percent), as well as the stabilization process due to the ageing, also increased. The rise of all these factors from a cycle to another intensifies the substructural cell-formation that in turn increases the dislocation density, the strain hardening and the absolute magnitude of compressive residual stresses in the surface layer of the parts submitted to this kind of processing.

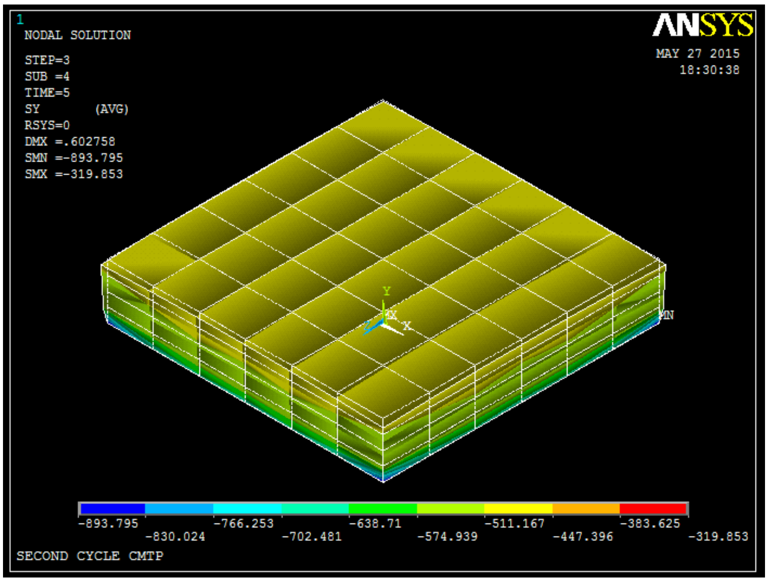

Figure 2. Average residual stress distribution "SY" after the second cycle of CMTP.

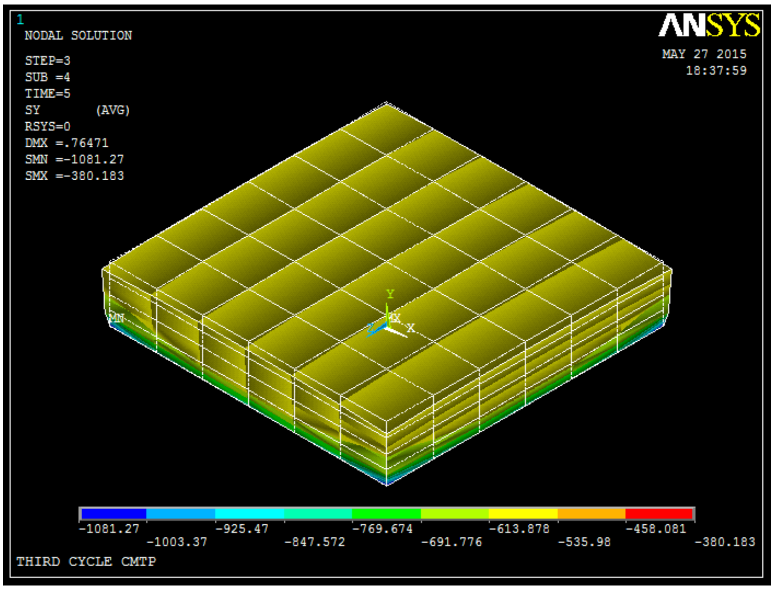

Figure 3. Average residual stress distribution "SY" after the third cycle of CMTP.

"Figure 4" shows the predicted residual stress profiles in y-axis direction after second and third modeled and simulated cycles of the cyclical mechanic-thermal processing (CMTP). In both cycles at small penetration depth, the residual stress profile shows that the maximum compressive residual stress is at the surface and decreases towards the tensile region. The predicted patterns of residual stress profiles closely match those measured data of similar treated surfaces in the literature (Larikov and Tijonov, 1985). At larger penetration depths the magnitudes of predicted compressive residual stresses are significantly reduced at the surface. However, the maximum compressive residual stresses occur at less than 0.1mm into the deformed region of the surface layer. The predicted hook shaped residual stress profiles resemble the characteristics of measured residual profiles obtained by several kind of surface treatments (Delgado, 2014).

From the done analysis the most significant is the fact that along the whole hardened layer one can appreciate the high realization degree of non-uniform plastic strain.

The evolution of normal component of stress tensor along the y-axis is presented in "Fig. 4". Maximum values of tension stress slightly and continuously increase and are not affected of releases. An important parameter, which is the compression normal stress on y-axis direction, indicates the degree of strain hardening of material superface layer and the depth of this layer points out the depth of strain hardening. Its values vary, after applying the third cycle of CMTP around 780 MPa, this magnitud is higher than the ultimate stress of given steel in supply state. Indeed, this revelation is not too simple, because of it is indicating that during the first stage of the CMTP, that is, for the all the plastic deformation processes in the surface layer continuously it is generated a great amount of dislocation, that constantly are in motion, but at the same time, and for the same cause, these grains begin to triturate, increasing their amount, therefore the amount of their boundaries also increases, and the grain boundaries constitute the main obstacles that retain the dislocation into each grain.

Into the grain, the generator mechanism of dislocation nonstop under the influence of plastic strain, increasing the dislocation density. After finishing this stage in each cycle of the processing, the steel increases its integral strength, and performance. However, this state is not stable, it is very sensitive mainly to tempeture variation during the part working. Keeping in mind this trouble (Oding *et al*., 1969; Gordienko, 1973), it is necessary to submit the parts to second stage of the processing: artiffitial ageing, in order to achieve the surface stability at forming the substructure, this means that during the ageing process the grain is subdivided in subgrains (each grain is subdivided in around 10^5 subgrains); the subgrains are separated among themselves through sub-boundaries. These sub-boundaries are constituted by dislocation cell substructure, within which almost not defects, that is, within the subgrains the material behaves itself almost like ideal metal (without defects), in fact, this is the cause that after cyclical mechanic-thermal processing the steel increases its strength up to the level of one third of its theoretical strength.

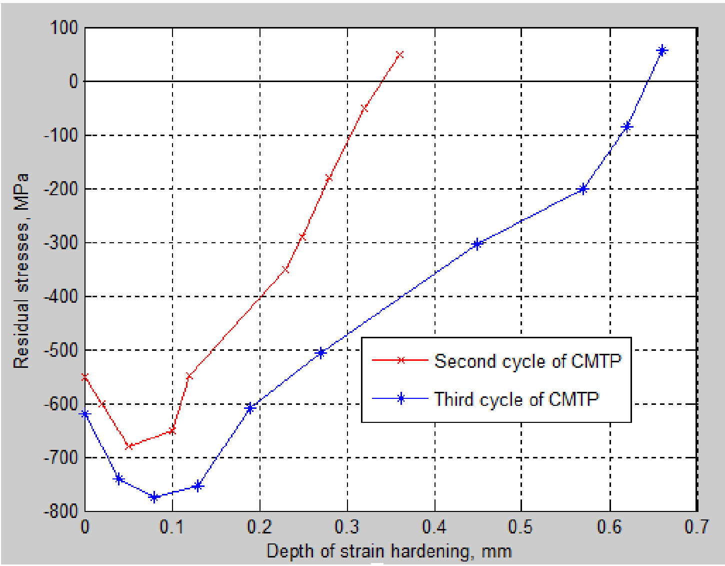

Figure 4. Dependency of the residual stress on the amount of cycles during the cyclical mechanic-thermal processing (CMTP)

4. CONCLUSIONS

- During this study, a completely new 3D model of cyclical mechanic-thermal processing had been simulated using the FEA program ANSYS, considered one of the best commercial software for the coupled-field analysis.
- The cyclical mechanic-thermal processing increases, strengthens and stabilizes the strain hardening and compressive residual stresses in the surface layers of steel parts.
- The modeling, simulation and analysis of results offer a comprehensive image of the cyclical mechanic-thermal processing.
- Each subgrain behaves itself as "pure metal" (Gordienko, 1973), as result of high density of retained dislocations into the grains and their rearrangement, forming the sub-boundaries and subgrains, whithin these last almost not dislocation.

5. REFERENCES

APDL, 2011. “Coupled field analysis guide”. Ansys Parametric Design Language. 19 Feb. 2015 < Ansys help system, v. 14.0>

Bagherifarda, S. and Guagliano, M., 2011. Influence of mesh parameters on FE simulation of severe shot peening (SSP) aimed at generating nanocrystallized surface layer. *Procedia Engineering*. Vol. 10, p. 2923–2930.

Delgado, S. Y., 2014. *Sub-microcrystalline structural state formation of low carbon steel and steel composites, during their thermomechanical processing* (in Russian). Ph.D. thesis, Ural Institute of Metal Physics, Yekaterinburg.

Gordienko, L.K., 1973. *Substructural hardening of metals and alloys* (in Russian). Nauka Issue, Moscow.

Guliaev, G. I., Fridman, Z. G. and Mozharenko, I. P., 1976. Heat resistant properties of 12Cr1MoV steel pipes, hardened by means of mechanic-thermal processing. *MITOM*, p.1-4.

Ivanova, V. S. and Gordienko, L. K., 1964. *New ways for increasing the strength of materials* (in Russian). Nauka Issue, Moscow.

Kukala, V. and Sahoo, S. K., 2013. Finite element analysis of ultrasonic vibratory tool and experimental study in ultrasonic vibration-assisted turning (UVT). *Advanced Materials Manufacturing & Characterization*, Vol. 3, No.8, p. 451-454.

Larikov, L. N. and Tijonov, A. B., 1985. *Substructural hardening of metals and diffraction investigation methods* (in Russian). Naukova Dumka, Kiev.

MacDonald, M. and Kulatunga, M. P., 2013. Finite element analysis of cold-forming steel with perforations subjected to compression loading. *Mechanics and Mechanical Engineering*, Vol. 17, No.2, p. 127-139.

Oding, I. A., Fridman, Z. G. and Zubarev, P. V. 1969. Mechanic-thermal processing of metals, like method for increasing their heat resistant capabilities (in Russian). *Collection: Metals in Actual Energetic Plants*, Moscow.

Oding, I. A., Zubarev, P. V. and Fridman, Z. G., 1961. Polygonization in metals (in Russian). *MITOM*, No. 1.

Savchenkov, E. A. and Aytkulov, P. P., 2005. Anti- corrosive properties of steel with cell-polygonal substructure (in Russian). *Bulletin of Orenburg State University*, No. 9, p. 179-183.

Szabracki, P., Bramowicz, M. and Lipinski, T., 2012. Development and verification of work hardening models for X2CrNiMoN25-7-4 super duplex stainless steel after sigma phase precipitation hardening used for FEM simulations. *Journal of Power Technologies*, Vol. 92, No. 3, p. 166-173.

Vishwakarma, P., Stalin John, M. R. and Arun Prasad, K. R. 2011. Evaluation of surface roughness for milling using FEM techniques. *International Journal of Advanced Engineering Technology*, Vol. II, No. III, p. 240-242.

Zemčík O., Chladil, J., Otoupalík, J. and Sedlák, J., 2013. Changes in the surface layer of rolled bearing steel. Proceedings in Manufacturing Systems, Vol. 8, No. 2, p. 99-104.

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