# Effect of thermo-mechanical treatments on mechanical properties and residual stresses in cold-drawn wire rods of eutectoid steel

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*Studies of mechanical properties and residual stresses in cold-drawn eutectoid steel bars with a diameter of 10.0 mm after patenting and drawing, with further short tempering under tension, are presented in this article. The changes in ultimate tensile strength, the relations between ultimate tensile strength and yield strength and the percentage elongation, in a range of treatment temperatures of 320-400°C and of tension force of 34300-58800 N were studied. Moreover, the residual stresses in steel bars after thermo mechanical treatments were evaluated.*

**KEYWORDS:** EUTECTOID STEEL - THERMO-MECHANICAL TREATMENT - MECHANICAL PROPERTIES - RESIDUAL STRESSES

## INTRODUCTION

High-strength eutectoid steel is widely used in manufacturing bars for critical pre-stressed reinforced concrete structures (building floor structures, bays, bridge footings, reinforced concrete piles, power transmission line supports, reinforced concrete sleepers, light towers, TV towers, etc.). Bars are characterized by high strength and definite level of plastic properties, and strict requirements for special properties. Global trends focus on the research of an efficient combination of various treatments to optimize the steel microstructure [1-3]. The high-strength bars are usually produced by cold drawing of patented eutectoid steel, with high levels of deformation [4]. As a result of such treatment, cold-drawn steel has a ferrite-cementite structure with an interlamellar spacing of 0.1 - 0.2 µm, and a cementite lamella thickness of 200 - 400 Å, and this microstructure gives the high strength properties. To ensure high values of relaxation resistance, bars are additionally thermo-mechanical treated (TMT). The most advanced option of such treatment is represented by short tempering of cold-drawn steel bars, using induction heating at 250-420°C with applied stretching force. In this case, tensile stresses rised up to 30-70% of ultimate tensile strength of cold-drawn steel bars. The mechanical properties and relaxation resistance of finished bars are correlated to the steel microstructure and level of residual stresses after thermo-mechanical treatment [5].

M. Elices studied the effect of residual stresses in cold-drawn eutectoid steel wire on the mechanical properties [6]. Atienza et al. studied the distribution of residual stresses in cold-drawn eutectoid steel wire, after thermo-mechanical treatment with various tension forces, in both longitudinal and transverse direction [7]. X-ray and neutron diffraction analysis were performed to study the relaxation features of an eutectoid steel after drawing and different types of final treatment [8-9]. L. Caballero et al. carried out experiments to determine the effect of temperature and stretching level of the commercial stress-relieving treatments on pre-stressed eutectoid steel wire with the aim of reducing stress relaxation [10].

The studies about the thermo-mechanical treatment of pearlitic steels showed that this treatment is very successful in reducing the residual stresses produced by drawing, especially in the surface area of the wire [11-12].

Although recent scientific papers focus on the thermo-mechanical treatment of cold-drawn eutectoid steel long products, including short induction tempering, there are only few studies on the effect of process parameters on changes in mechanical properties and residual stresses, especially when the diameter of eutectoid steel products increases.

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The present paper shows the results of the study about the thermo-mechanical treatment parameters effect on the mechanical properties and residual stresses in a cold-drawn eutectoid steel wire rod with a 10.0 mm diameter.

## MATERIALS AND RESEARCH METHODS

A wire rod of steel grade 80, which initially was 15.5 mm in diameter, was used. The steel chemical composition is given in Table 1.

| C | Si | Mn | P | S | Cr | Ni | Cu | Al | V | B |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.80 | 0.29 | 0.62 | 0.010 | 0.0025 | 0.04 | 0.02 | 0.032 | 0.02 | 0.011 | 0.002 |

**Tab. 1** - Chemical composition of steel grade 80 (wt %).

The patenting of the wire rod was carried out in an industrial line and it consisted in heating at 970°C and quenching in a molten lead bath at 550°C with a patenting speed of 4.8 m/min. The patented wire rod was subjected to a cold drawing process until to obtain a diameter of 10.0 mm with a total deformation degree of 58.5 %. Then, the cold-drawn wire rod surface was treated to get three-sided die-rolled section, to increase binding with concrete, and subjected to thermo-mechanical treatment. Different process parameters of the thermo-mechanical treatment (TMT) were studied: tension force and induction heating temperature. The tensions force was varied between the values of 34300 and 58800 N, whereas the heating temperature between 320 and 400°C for a total of 9 tests, as summarized in Table 2. The treatment speed was 50 m/min. After the induction heating, the wire rod was subjected to water cooling at a water temperature of 25°C and water pressure of 300 kPa. Mechanical tests of samples were performed using standard methods.

| sample | tension force (N) | temperature (°C) |
|---|---|---|
| 1 | 34300 | 320 |
| 2 | | 360 |
| 3 | | 400 |
| 4 | 46550 | 320 |
| 5 | | 360 |
| 6 | | 400 |
| 7 | 58800 | 320 |
| 8 | | 360 |
| 9 | | 400 |

**Tab. 2** - Studied thermo-mechanical treatment modes of wire rod.

Metallographic samples were prepared using standard methods, including mechanical polishing and etching with Nital 4%. Qualitative and quantitative microanalyses were performed using a Meiji Techno microscope and with the image computer analysis system Thixomet Pro. The scanning electron microscopic (SEM) analysis of samples was performed with a JEOL JSM-6490 LV electron microscope at an accelerating voltage of 30 kV in both secondary and backscattered electrons mode.

All the samples were subjected to residual stresses measurements in both longitudinal and transversal direction respect to the drawing one with a Siemens D500 X-ray difractometer, adopting as material-related elastic properties the ferrite constants E = 210 GPa, $\upsilon = 0.29$ and an anisotropy factor of 1.39 (from XRD database). The $\sin\psi^2$ method was employed to evaluate the stresses, using the Cr-K$\alpha$ radiation on the ferrite-(200) peak, located at $2\theta = 106°$, and a fitting procedure implemented on the XRD software (Marquardt fit of the peaks and stress calculation by linear or elliptic fit, depending on peak positions displacement).

## RESULTS AND DISCUSSION

### Microstructure and mechanical properties

The microstructures of the wire rod in the initial hot rolled state, after patenting and drawing, are shown in Fig. 1a, b, c. The microstructure was a ferrite-carbide mixture with various degrees of dispersion, namely from sorbitic pearlite to thin-lamellar pearlite. Although steel had a eutectoid mixture, the sample structure contained some ferrite (dark areas in Fig. 1b) due to presence of boron, contributing to generation of $\alpha$-phase. Changes in interlamellar spacing of the ferrite-carbide mixture during treatment are shown in Fig. 2. The average interlamellar spacing in initial hot rolled steel was 0.27 μm (Fig. 2a). After patenting and drawing, the interlamellar spacing decreased to 0.16 μm and 0.12 μm, respectively (Fig. 2b, c). The drawing process entailed the grain refinement, resulting in fragmented microstructures, where deformation effects can be observed (Fig. 2c).

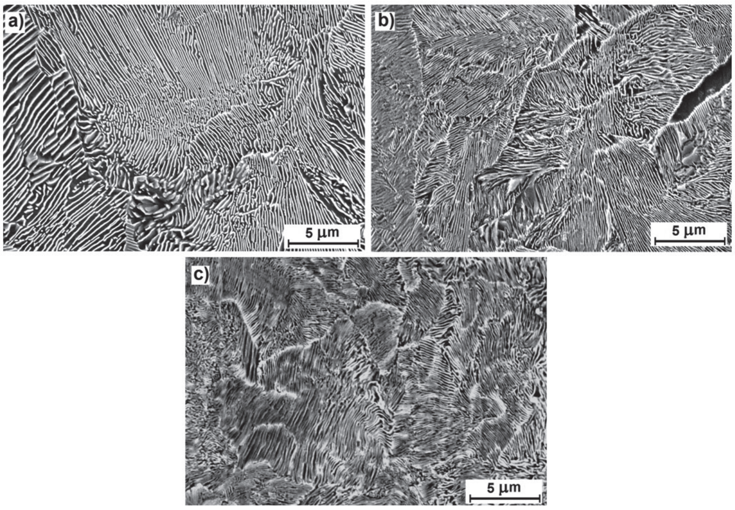


**Fig. 1** - SEM-SE images of steel microstructure: a) initial hot rolled state; b) after patenting; c) after drawing

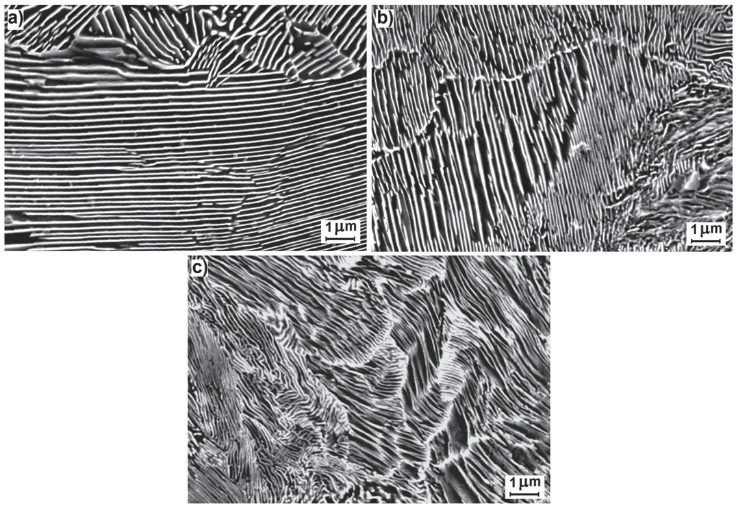


**Fig. 2** - Structure of the perlite: a) initial hot rolled state; b) after patenting; c) after drawing

However, the optical microscopy and the scanning electron microscopy analysis of the thermal-mechanical treated samples did not reveal significant differences in the microstructure of the steel treated with various temperatures and forces. (Fig. 3).

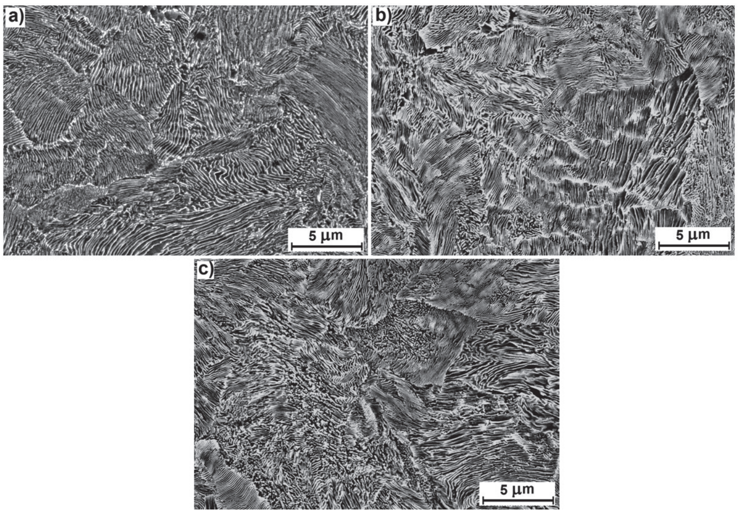


**Fig. 3** - Steel microstructure in the cross-section of samples after thermo-mechanical treatment:
a) sample n. 1; b) sample n. 3; c) sample n. 6 (see Table 1)

The results of the mechanical tests showed that the values of ultimate tensile strength and percentage elongation increased after the thermo-mechanical treatment, for all process parameters considered, in comparison with the sample before the TMT (Fig. 4). The most significant role in such trend is assigned to temperature. It should be noted that a significant increase of the ultimate tensile strength, about 6.3%, occurred for TMT carried out at 250°C, for all tension forces studied (Fig. 4a). Further increase in treatment temperature up to 400°C led to a gradual smooth reduction (5%) of ultimate tensile strength, in comparison with the values obtained at 250°C.

Steel plasticity $\delta_{10}$ increased with temperature, and the major increase (45-64 %) was exhibited in the range of 250 - 320°C (Fig. 4b).

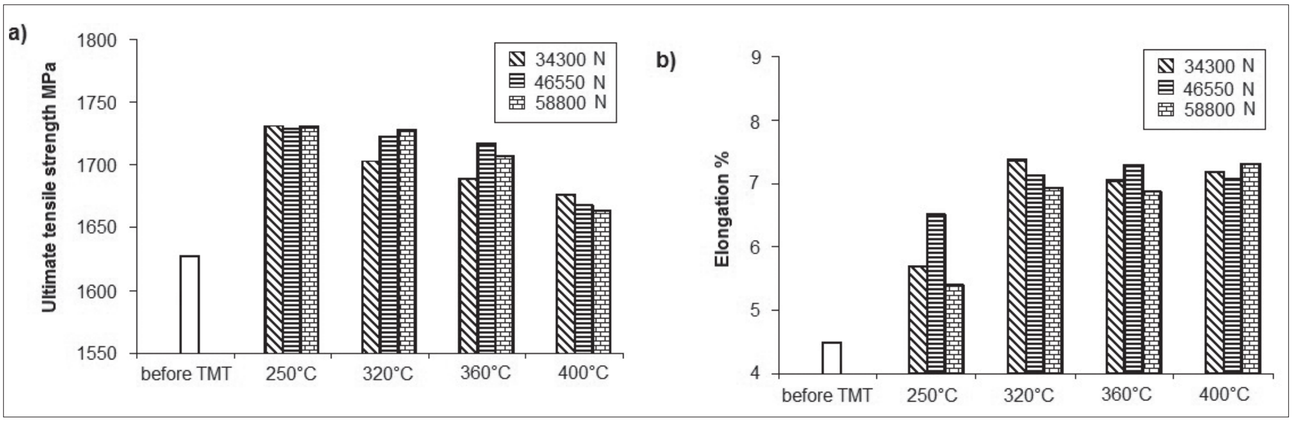


**Fig. 4** - Effect of thermo-mechanical parameters on mechanical properties of eutectoid steel: a) Ultimate tensile strength; b) percentage elongation of steel after rupture

These results showed that tension force did not significantly affect the ultimate tensile strength and percentage elongation of eutectoid steel. In the temperature range of 250 - 400°C, the changes in tension force from 34300 to 58800 N determined the maximum difference of 30 MPa in ultimate tensile strength, and of 1.12% in the percentage elongation.

In comparison with the sample before TMT, the parameter $\sigma_B/\sigma_{0,2}$ (ratio between ultimate tensile strength UTS and yield strength YS) sharply decreased for the treatment at 250°C, after that a uniform increase in a range of 320 - 400°C was observed, for all the values of tension force (Fig. 5).

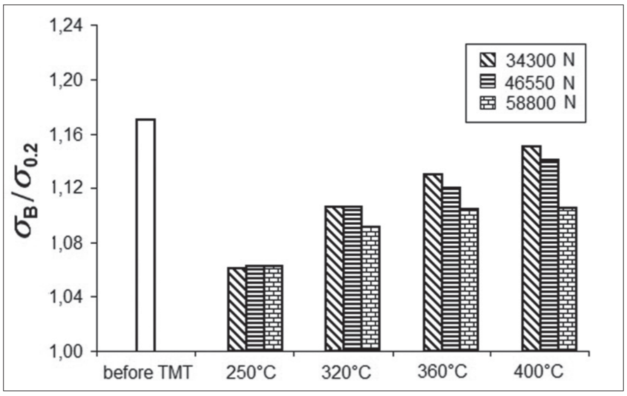


**Fig. 5** - Effect of thermo-mechanical parameters on ratio between ultimate tensile strength and yield strength

Parameter sensitivity to processing treatment increased when treatment temperature and tension force increase at the same time. Within a range of 34300 - 58800 N tension force had almost no effect on relation between UTS and YS. However, in a range of 320 - 400°C the role of tension force became apparent to a bigger extent.

## Residual stresses

The results evidenced that all the received samples were subjected to compressive residual stresses in both longitudinal and transverse direction (Fig. 6). However, while the longitudinal stresses can be represented by a pure-σ (compressive) stress in all samples, a τ (shear) component was always observed in the transverse direction, except for one case where it resulted missing (Table 3).

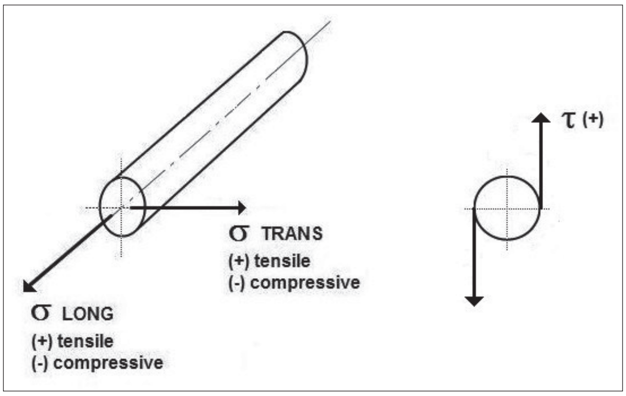


**Fig. 6** - The sketch of wire with stress orientations.

| sample | tension force (N) | temperature (°C) | measured residual stresses (MPa) | | | principal stresses (MPa) | | | σ eq. (Von Mises) (Mpa) |
|---|---|---|---|---|---|---|---|---|---|
| | | | σ (long) | σ (trans) | τ (trans) | σ I | σ II | σ III | |
| 1 | 34300 | 320 | -685 | -622 | -169 | 43.0 | -665.0 | -685.0 | 718 |
| 2 | | 360 | -689 | -693 | 98 | 13.6 | -689.0 | -706.6 | 712 |
| 3 | | 400 | -736 | -695 | -21 | 0.6 | -695.6 | -736.0 | 717 |
| 4 | 46550 | 320 | -575 | -651 | -55 | 4.6 | -575.0 | -655.6 | 624 |
| 5 | | 360 | -702 | -683 | 0 | 0.0 | -683.0 | -702.0 | 693 |
| 6 | | 400 | -783 | -679 | -74 | 8.0 | -687.0 | -783.0 | 748 |
| 7 | 58800 | 320 | -665 | -657 | -90 | 12.1 | -665.0 | -669.1 | 679 |
| 8 | | 360 | -760 | -682 | 149 | 31.1 | -713.1 | -760.0 | 769 |
| 9 | | 400 | -947 | -701 | 82 | 9.5 | -710.5 | -947.0 | 863 |

**Tab. 3** - Results of the residual stresses measurements.

Two examples of the fitting results in the two direction are presented in Fig. 7 and must be considered valid for all the specimens, even if in different extent; as can be seen, the longitudinal data were better fitted by a linear interpolation, while the transverse ones always required elliptical fittings. Note that, in some cases, the observed shear component cannot be ignored, since its absolute value reached values around 100 MPa or considerably greater (Table 3).

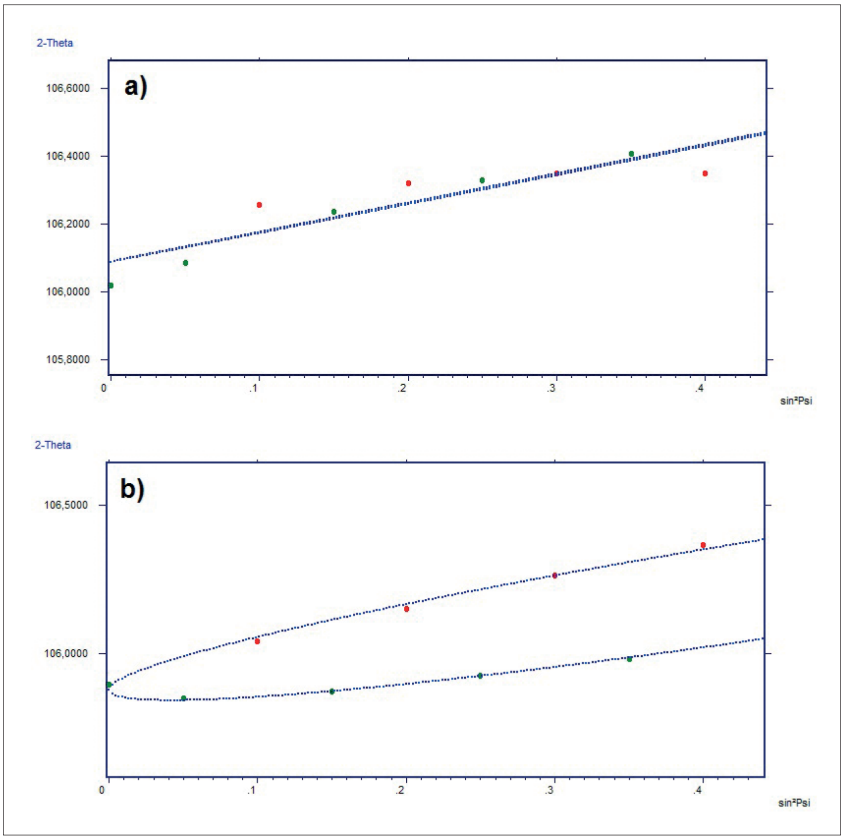


**Fig. 7** - Sample n.8: longitudinal (a) and transversal (b) fitting curves.

By plotting the data obtained in the longitudinal direction (Fig. 8), a general decreasing trend in the measured residual stresses was observed by rising the process temperature (this means an increased residual compression stress). Respect to the others, the first set of samples (tension force-grouping) showed a different global trend, with the first specimen affected by an increased residual stress if compared to other materials processed at 320°C; note that sample n.1 also possesses the highest measured shear stress. Conversely, the medium-loaded sample seemed to possess the most likelihood trend, exhibiting a linear stress intensification by increasing the process temperature. However, except for sample n.1, it is possible to assert that with rising temperature and tension force the material is increasingly affected by residual stresses, which are intimately related to acting force and cooling conditions.

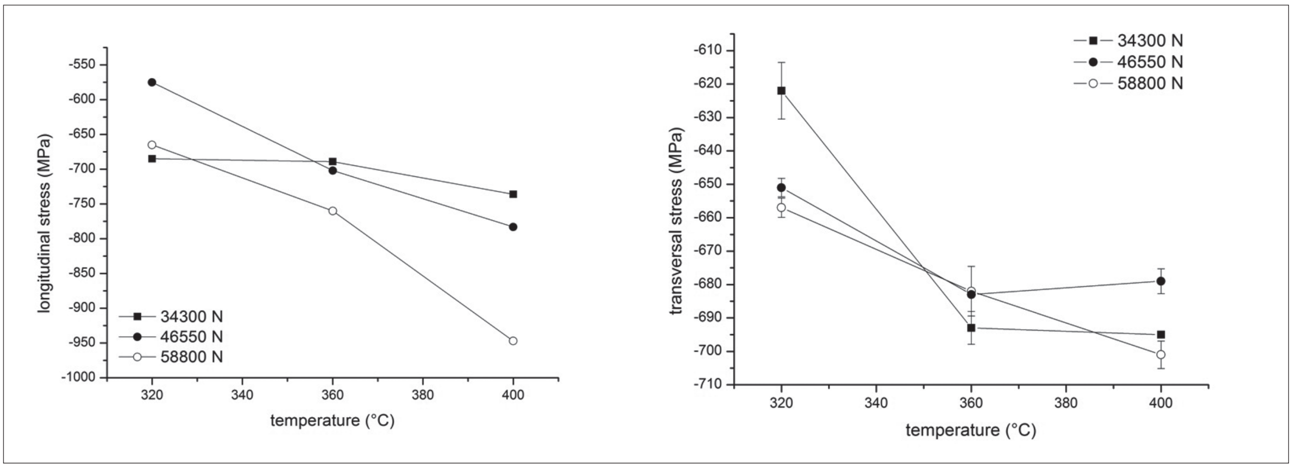


**Fig. 8** - Measured longitudinal and transversal residual stresses.

The transverse residual stresses are plotted in Fig. 8, in which the error bands must not be intended as standard deviations, but are proportional to the measured shear component. Here, in the firsts two sets of samples, a flattening of the curves at higher temperatures was observed but, supposing that the «46550 N» set exhibited the more likelihood trend, sample n.1 fall out again from the global trend. In this case, the maximum-loaded set was different from the others, showing an increasing compressive stress, and sample n.8 can be considered as anomalous in order to obtain a L-shaped curve. As a matter of fact, sample n.8 possesses the second greatest shear component, which can to some extent confirm its outlier displacement.

For the complete stress analysis, the Mohr's approach has been taken into account, allowing for the determination of the principal stresses acting on the samples (Table 3). The most critical results were found for the sample n.9, being processed at the highest temperature by applying the maximum tension force (Fig. 9). On the contrary, sample n.4 was found to be with the less residual stresses.

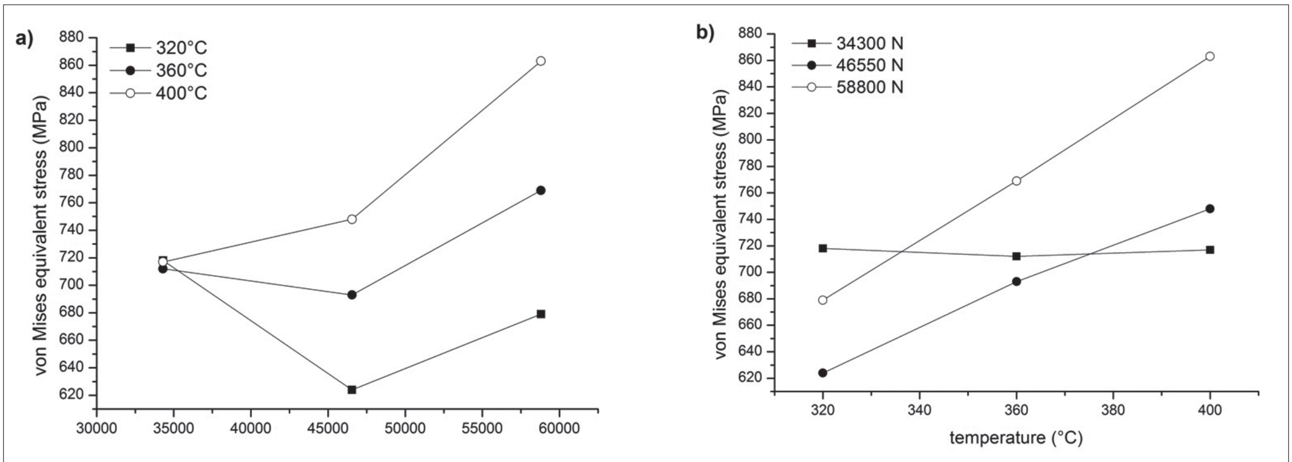


**Fig. 9** - Equivalent residual stresses as a function of temperature (a) and load (b).

Similar trends were observed in the samples processed at 46550 N and 58800 N (tension force-grouping), whereas a flat global trend was observed for the first set, excluding the increased shear stress in sample n.1. Considering a temperature-grouping, the corresponding curves in Fig. 9 are even more translated toward high equivalent-stress conditions as the process temperature is raised, thus highlighting the very critical role of such parameter in the observed residual stress components. Note that processing the samples at 320°C did not alter the measured equivalent stress, even if the shear component contributions must be taken into account, depending on the material purpose.

## CONCLUSIONS

In this work, the microstructure, the mechanical properties and residual stresses in high-strength cold-drawn eutectoid wire rod, with a diameter of 10.0 mm, were studied after the thermo mechanical treatments, carried out at different tempering temperature (250-400°C) and with various tension force (34300-58800 N).

In comparison with the initial state of steel, after patenting and drawing, all thermo-mechanical treatments induced an improvement in the ultimate tensile strength and percentage elongation. The maximum value of the ultimate tensile strength was observed for the treatment carried out at 250ºC, and the further increase in temperature, up to 400ºC, entailed a gradual smooth reduction. Steel plasticity $\delta_{10}$ increased of 45 - 64 % in the range of 250 - 320ºC.

The results showed that temperature and the tension force affected the mechanical properties of cold-drawn wire rod, but in different ways. All the temperatures significantly influenced the trend of the mechanical properties of cold-drawn steel, whereas the effect of the tension force became important only in a range 46550-58800 N and for the temperature between 360-400ºC.

The compressive residual stresses, in both longitudinal and transverse directions, increased with increasing tension force and temperature. Compressive residual stresses had the most favorable effect on relaxation resistance of eutectoid wire rod during their application.

## REFERENCES


[1] Langdon Terence G. Twenty-five years of ultrafine-grained materials: Achieving exceptional properties through grain refinement. Acta Materialia 2013, Vol. 61, no. 19, pp. 7035-7059.

[2] Han K., Edmonds D., Smith G. Developments in ultra-high-carbon steels for wire rod production achieved through microalloying additions. Materials & Design 1993, Vol. 14, no 1, pp. 79-82.

[3] E.M. Talef, J.J. Lewandowski and B. Pourladian. Microstructure-property relationships in pearlitic eutectoid and hypereutectoid carbon steels. JOM 2002, Vol. 54, no.7, pp 25-30.

[4] Lebedev, V.N., Korchunov, A.G., Chukin, M.V. Production of stabilized high-strength reinforcement steel for the new generation of ferroconcrete railroad ties. Metallurgist 2011, Vol. 55, no.1-2, pp. 54 - 58.

[5] J.M. Atienza. Role of residual stresses in the stress relaxation of prestressed concrete wires. Journal of Materials in Civil Engineering 2007 , Vol.19, no. 8, pp.703-707.

[6] M. Elices. Influence of residual stresses in the performance of cold-drawn pearlitic wires. Journal of Materials Science 2004. Vol.39, no 12, 3889 - 3899.

[7] J.M. Atienza, M. Elices, J. Ruiz-Hervias, L. Caballero and A. Valiente. Residual stresses and Durability in cold drawn eutectoid steel wires. Metals and Materials International 2007, Vol. 13. no. 2, pp. 139 - 143.

[8] J.M. Atienza, M. Elices. Influence of residual stresses in the stress relaxation of cold drawn wires. Materials and Structures. June 2004. Vol. 37, pp. 301 - 304.

[9] M.L. Martinez-Perez, F.J. Mompean, J. Ruiz-Hervias. Residual stress profiling in the ferrite and cementite phases of cold-drawn steel rods by synchrotron X-ray and neutron diffraction. Acta Materialia 2004. Vol.52, no18, pp.5303-5313.

[10] Caballero L., Atenza J., Elices M. Thermo-mechanical treatment effects on stress relaxation and hydrogen embrittlement of cold drawn eutectoid steels. Metals and material international. 2011, Vol. 17, no.6, pp. 899-910.

[11] F. Yang, J.Q. Jiang, Y. Wang, C. Ma, F. Fang, K.L. Zhao, W. Li. Residual stress in pearlitic steel rods during progressively cold drawing measured by X-ray diffraction. Materials Letters May 2008. Vol. 62, no 15, pp. 2219-2221.

[12] J. Ruiz-Hervias, V. Luzin, H. Prask, T. Gnaeupel-Herold, M. Elices. Effect of thermo-mechanical treatments on residual stresses measured by neutron diffraction in cold-drawn steel rods. Materials Science and Engineering A. 2006, Vol.435-436, pp.725-735