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Experimental determination of residual stresses in the hard-faced layers after hard-facing and tempering of hot work steels

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Abstract

The procedure for experimental determination of the longitudinal and lateral residual stresses in the multi-layer hard-faced plates, made of the hot work tool steel used for forging dies manufacturing, is presented in this paper. The objective of this research was to establish the influence of the multi-layer hard-facing on residual stresses in the thin and thick plates, which could later, in exploitation, cause the appearance of cracks and fracture. The influence of tempering on decreasing the residual stresses was monitored, as well. The plates were hard-faced in three layers, while the stresses were measured by the magnetic method. The obtained results have shown, among others, that the residual stresses are higher in the thick plates, as well as that the proper regime of the heat treatment can significantly reduce the level of residual stresses.

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Keywords: hard-facing; hot work tool steel; residual stresses; tempering;

Nomenclature

s	plate thickness
d_e	electrode diameter
I	hard facing (surfacing) current
U	hard facing (surfacing) voltage

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v_{hf}	hard facing speed
q_l	input energy
μ_r	magnetic permeability
B	average width of the whole hard-faced layer
b	average width of a single hard-faced layer caterpillar
H	average height of the whole hard-faced layer
h	average height of a single hard-faced layer caterpillar

1. Introduction

The procedure for experimental measurements of the residual stresses that appeared in the multi-layer hard-faced steel plates is presented in this paper. The plates are made of the hot work tool steel, which is aimed for manufacturing the forging dies. The hard-facing of plates of two different thicknesses was done: the thin plates whose thickness was 7.4 *mm* and thick plates whose thickness was 29 *mm*. The hard-facing was done in three passes (layers). Taking into account the importance of the heat treatment for decreasing or eliminating the residual stresses, the influence of tempering on level of those stresses was experimentally monitored, as well. In some previous publication, authors of this paper were investigating influence of the multi-pass hard-facing [1] and tempering [2] on level of deformation of samples. It was shown that deformations appear and increase linearly with number of passes, as well as that the level of residual stresses could be lowered by tempering, especially for the thick plates.

Some authors, like Yang et al. [3], were dealing with numerical analysis of residual stresses in the hard-faced layers and influence of martensite on the level of residual stresses. They established the numerical model, which was verified experimentally and concluded that decreasing of the martensite transformation (M_s) starting temperature leads to decrease of the residual stresses. Wua et al. [4] have also investigated possibility for numerical simulations for determination of the residual stresses' level and possibilities for their eliminating. It was concluded that the residual stresses' level depends on several factors, like the heat transfer coefficient, the thermal expansions of the materials, the thickness of the base metal and the preheating temperature. The significant influence on the lowering the level of residual stresses is exhibited by preheating, or depositing of the plastic inter-layer of the stainless steel between the hard-faced layer and the base metal, what was proven as very efficient by Arsic et al. [5]. The presented results also indicate that the numerical simulation method present a useful and convenient means for investigating the residual stresses of the hard-facing process. Deng et al. in [6] have analyzed the influence of the temperature field on stresses in the welded parts made of the stainless steel. It was established, by simulation, that welded joint zone is the most critical from the aspect of the residual stresses and the correctness of the numerical model was verified by experiments. The high level of residual stresses does not appear only when the conventional technologies are applied, but it can also appear when the modern hard-facing methods are used, as shown by Yilbas et al. [7]. The importance of the residual stresses in the hard-faced – revitalized machine parts is great, since they can influence integrity of the whole structure or the plant. In the case of the local exceeding of the permissible stresses (the material yield stress), the residual stresses could lead to drop of the material's impact toughness, as presented by Burzić et al. [8] or even to appearance of a crack, which could cause the fracture of the responsible machine parts, like the rotational dredger [9-10] or the forging tools [11-16]. For those parts, the hard-facing is almost dominant technology of revitalization, as well for their parts like heavy haul locomotive wheels [21], parts of construction mechanization [22] or tools used in the confectionery industry [23].

The objective of this paper was to point to appearance and presence of the residual stresses in the hard-faced layers and to define the influence of the multi-layer hard-facing procedure with subsequent tempering on the level of residual stresses.

2. Selection of the model (for the thin and thick plates)

Samples in the form of the thin and thick plates were used in order to determine the level of residual stresses. The selected plates (dimensions 394×192×7.4 *mm* - 4 pieces and 394×192×29 *mm* - 3 pieces) were tempered and then flatten by grinding. The base metal was the hot work steel 56NiCrMoV7, which is the most frequently used for forging dies.

The chemical composition and mechanical properties of this steel are given in Tab. 1. The plates were hard-faced according to technology presented in papers [14-16], by depositing of the three caterpillars in the middle of the plates, by one, two and three passes, Fig. 1. The hard-facing parameters are given in Tab. 2, while the speed of hard-facing was changed for each pass. The preheating and the inter-pass temperatures were controlled by the digital measuring device Tasthoterm, namely by the thermo-chalks. The thin plates were hard-faced by the UTOP 38 (DIN 8555: E3-UM-40T) electrode of diameter Ø 3.25 *mm* and UTOP 38 of diameter Ø 2.5 *mm*, while the thick plates were hard-faced by the UTOP 55 (DIN 8555: E6-UM-60T) electrode of diameter Ø 5.0 *mm*.

Table 1. Chemical composition, mechanical properties and microstructure of 56NiCrMoV7 steel [2, 17]

Steel mark	Chemical composition, %								
	C	Si	Mn	P	S	Cr	Ni	Mo	V
	0.55	0.3	0.7	0.035	0.035	1.1	1.7	0.5	0.12
	Mechanical properties and microstructure								
56NiCrMoV7	Soft tempering				Tempering				BM Microstructure
	t, °C	HV_{max}	R_m, MPa	$R_{p0.2}$, MPa	t, °C	HRC	R_m, MPa	$R_{p0.2}$, MPa	
	670-700	250	≈1200	1040	400-700	50-30	≈1600	≈1450	M + B (interphase)

Table 2. Hard-facing parameters

Plate #	Thickness *s, mm*	Number of layers	Electrode diameter d_e, *mm*	Hard-facing current, I, A	Voltage, U, V	Hard-facing speed, v_{hf}, *mm/s*	Input energy, q_l, *J/mm*
1	29	2	5.00	190	29	≈ 2.3	1916.5
2	29	3	5.00	190	29	≈ 2.3	1916.5
3	29	1	5.00	190	29	≈ 2.4	1836.7
4	7.4	1	3.25	115	26	≈ 2.6	920.0
5	7.4	2	3.25	115	26	≈ 1.7	1407.0
6	7.4	3	3.25	115	26	≈ 2.5	956.8
6*=6*	7.4	1	2.5	80	23	≈ 2.3	640.0

*Plate for calibrating the measurement sample

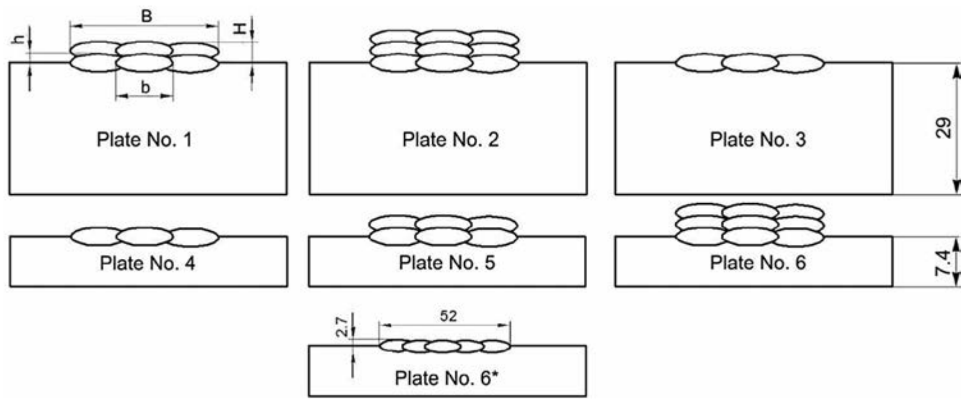

Fig. 1. Plate hard-facing schematics.

After the hard-facing, the plates were tempered at 520 ºC for the period of 2 *h*, primarily to decrease the level of residual stresses and deformations. The heat treatment regime and tempering temperature are considered to be optimal, since they enable obtaining of the optimal mechanical properties of the hard-faced layers [18, 19].

Geometrical characteristics (average values) of a single caterpillars and of the whole hard-faced layer are given in Tab. 3. During the deposition of the caterpillars, their partial re-melting was performed (approximately 1/3 *b*).

3. Determination of residual stresses after the hard-facing and tempering

The residual stresses were measured by the magnetic method. The principle of this method is based on dependence of the Ferro-magnetic materials permeability, μ_r on material's deformation, caused by the stress state, which enables recording of the instantaneous stress state in the material. Advantages of the method are the fast and efficient operation, possibilities for the field measurements, while its main deficiencies are the somewhat less accuracy of measurements and, of course, being applicable exclusively to Ferro-magnetic materials.

Table 3. Geometrical characteristics of the hard-faced layers

Plate #	Thickness s, *mm*	Number of layers	Hard-faced layer dimensions, *mm*			
			b_{av}	h_{av}	B_{av}	H_{av}
1	29	2	≈ 13	3.62	28-38.4	5.91
2	29	3	≈ 13	3.53	27.2-33.6	8.37
3	29	1	≈ 13	3.43	23.7-27.6	3.43
4	7.4	1	≈ 10	2.83	19.4-25.4	2.83
5	7.4	2	≈ 10	2.91	23.7-28.8	5.36
6	7.4	3	≈ 10	3.1	22.1-28.9	8.5
$6^1=6^*$	7.4	1	≈ 8.5	2.7	52	2.7

The residual stresses were recorded by the SMMT-1 device. It enables determination of the intensity and direction of the principal stresses. The probe measures the averaged values of stresses along the ≈ 10 *mm* length and up to ≈ 0.5 *mm* depth. Before the measurement, the device has to be calibrated by the special calibrating sample. Before the measurements, the sample plates were demagnetized. The stresses were measured along the characteristic lines, longitudinally along the III-III direction and in laterally along the IV-IV, V-V and VI-VI lines [2]. For the thick plates (1, 2 and 3) the stresses were measured in the hard-faced layers, as well, while for the thin plates that was not done, due to prominent deformations and also due to somewhat smaller total width of the hard-faced layers.

4. Results

Results of residual stresses measurements, in the lateral and longitudinal directions, for all the six hard-faced plates, before and after tempering, are presented in Figs. 2 to 7. The lateral stresses for the plate # 2 (Fig. 3) were not measured due to curving of the caterpillar. Obtained stress distribution was expected and in agreement with other researches [3-6].

5. Discussion and conclusions

Some very important facts resulted from the detailed analysis of these experimental investigations, which can usefully serve for definition of the hard-facing technology and subsequent heat treatment. Those remarks can contribute to improvement of the tools' regeneration procedure. The main conclusions are as follow:

- Distribution of the lateral stresses is in compliance with the data from literature [20, 21] (Fig. 3b), while the distribution of the longitudinal stresses has somewhat different form (Fig. 7b);
- The measured values of the residual stresses for the hard-facing of the thick plates are higher than the values for the thin plates;
- Tempering leads to lowering of the residual stresses in almost all the cases (Fig. 2c); that proves the necessity of this type of heat treatment, though in some cases the stress changes sign (from tensile changes to compressive, Fig. 5d, and vice-versa);
- The proposed way of tempering results in more symmetric stress distribution with respect to the hard-faced layers (Figs. 4b and 5c); The measured residual stresses are significantly lower than the yield stress of the base metal, thus lower than the yield stress of the hard-faced layer, what verifies the justification of the applied technology, selected

procedure and the heat treatment regime.

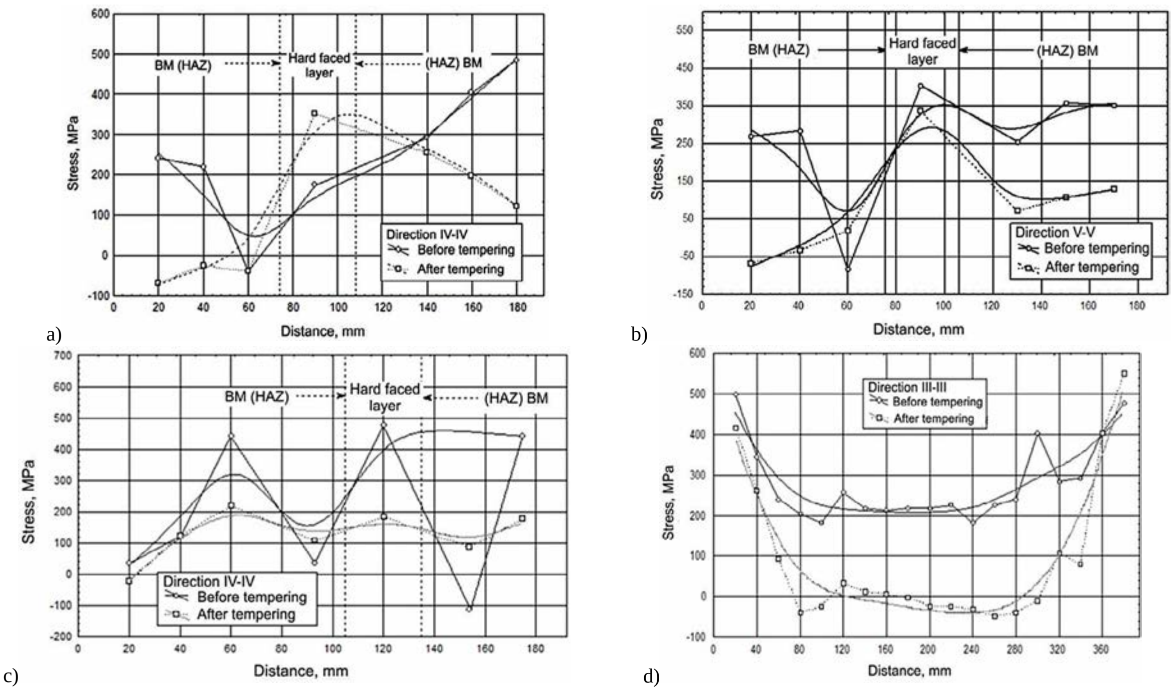

Fig. 2. Distribution of the lateral (a, b, c) and longitudinal (d) stresses before and after tempering – plate # 1.

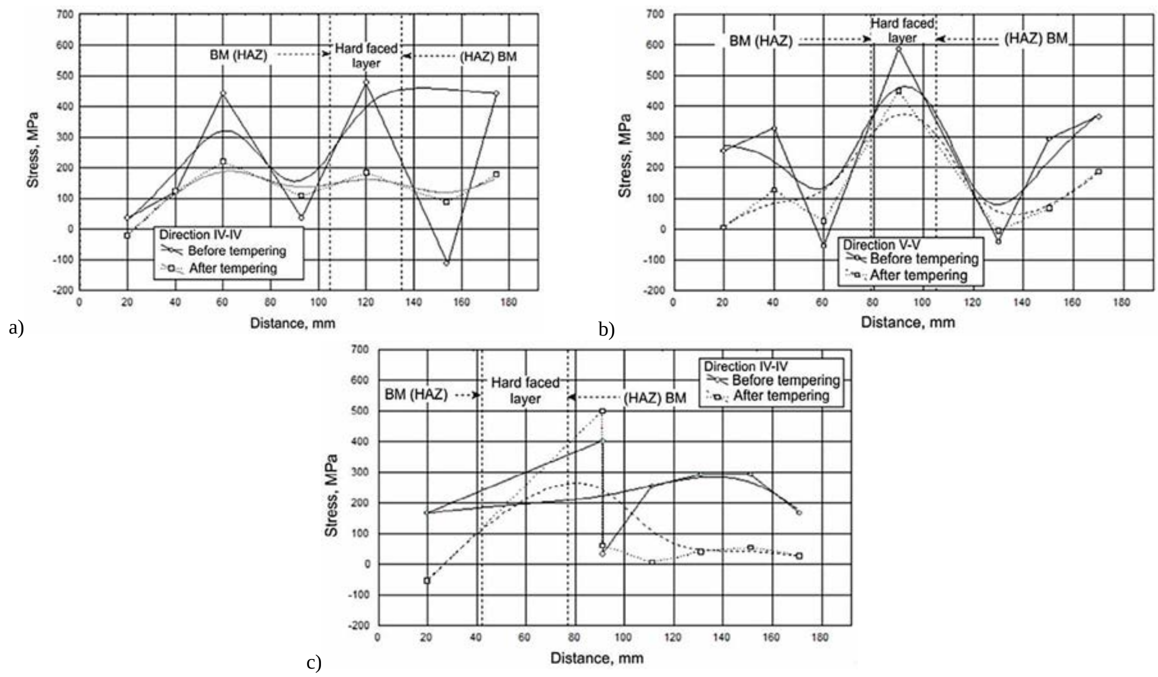

Fig. 3. Distribution of the lateral (a, b, c) stresses before and after tempering – plate # 2.

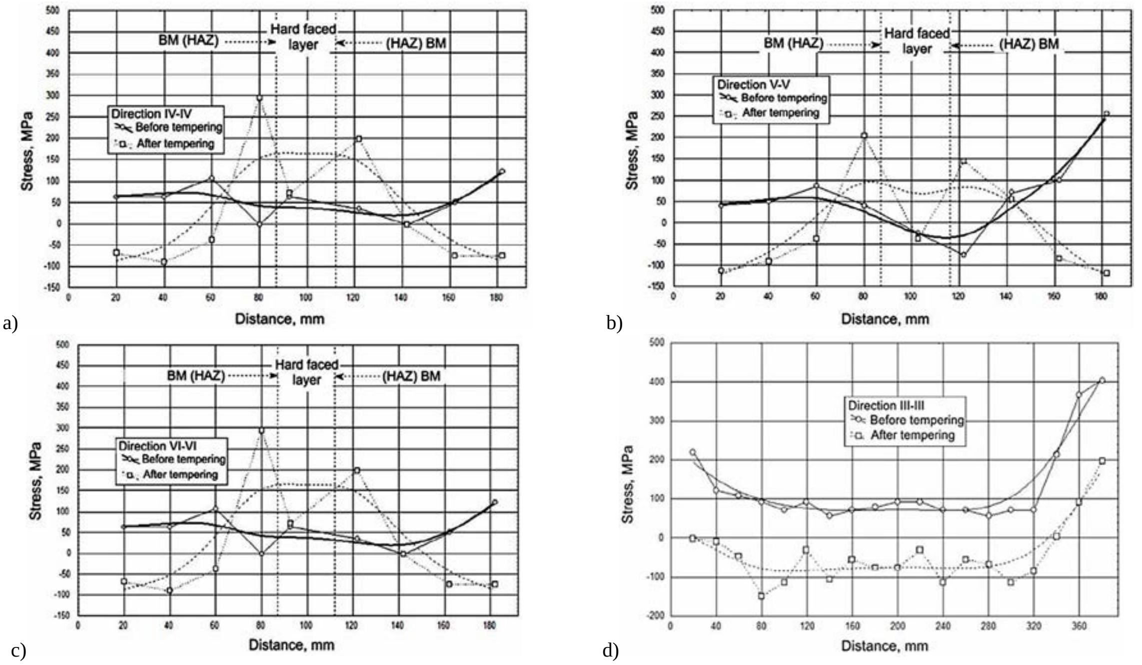

Fig. 4. Distribution of the lateral (a, b, c) and longitudinal (d) stresses before and after tempering – plate # 3

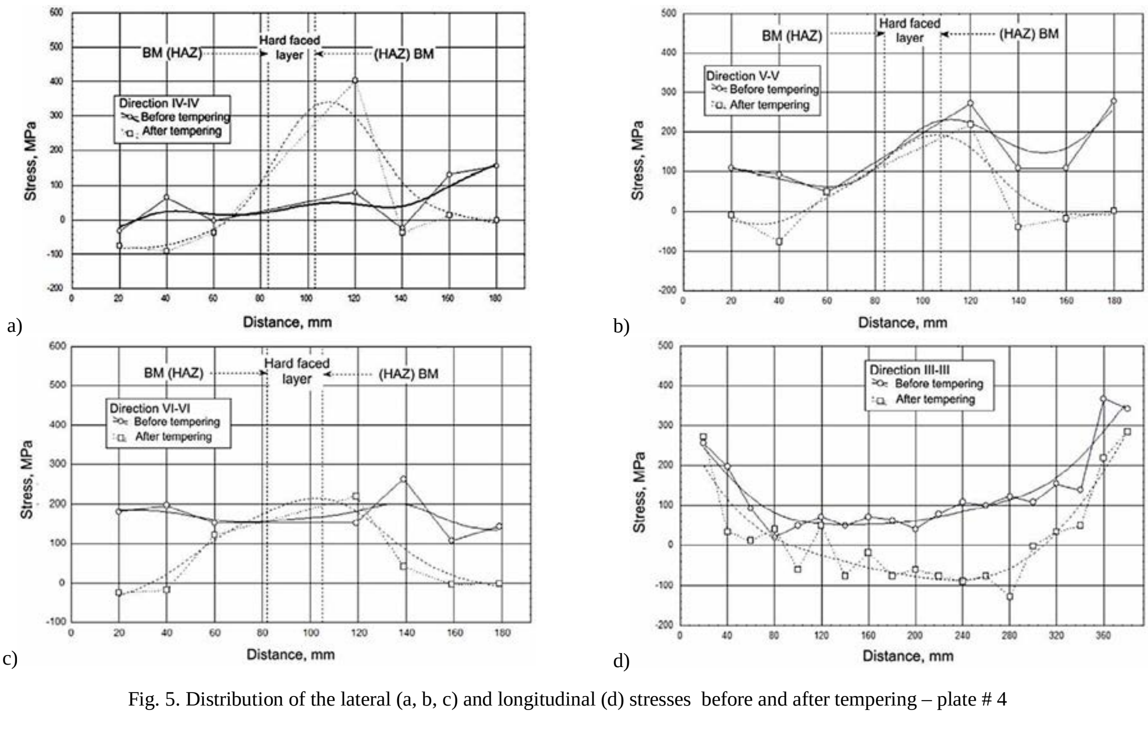

Fig. 5. Distribution of the lateral (a, b, c) and longitudinal (d) stresses before and after tempering – plate # 4

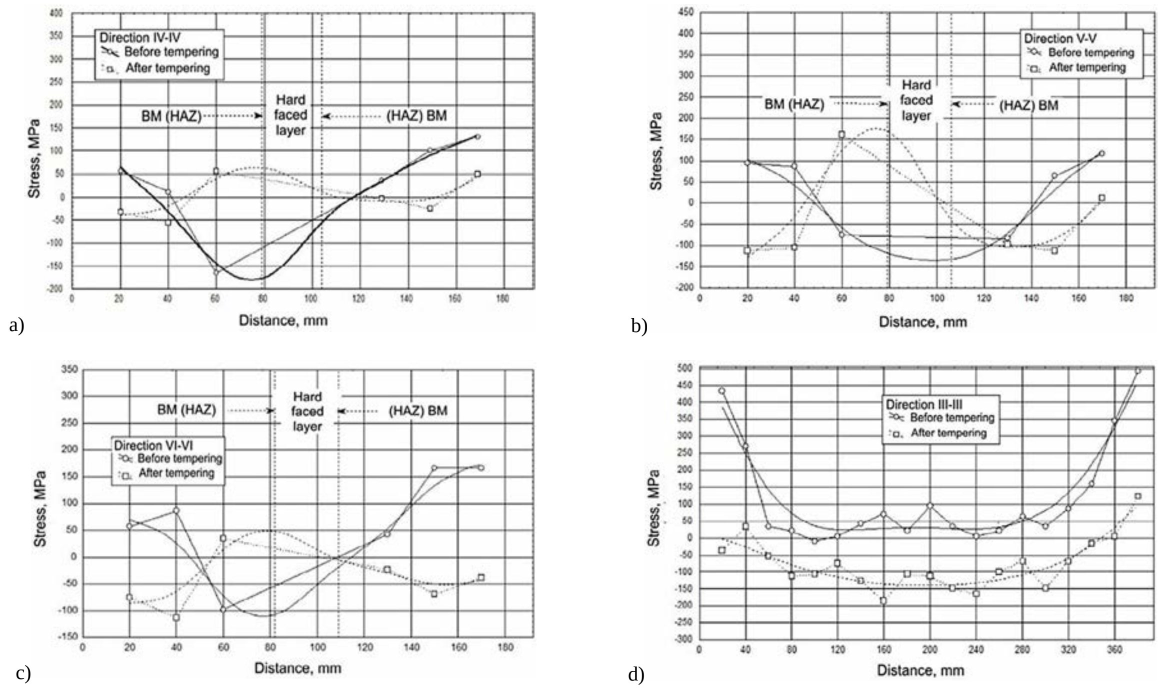

Fig. 6. Distribution of the lateral (a, b, c) and longitudinal (d) stresses before and after tempering – plate # 5

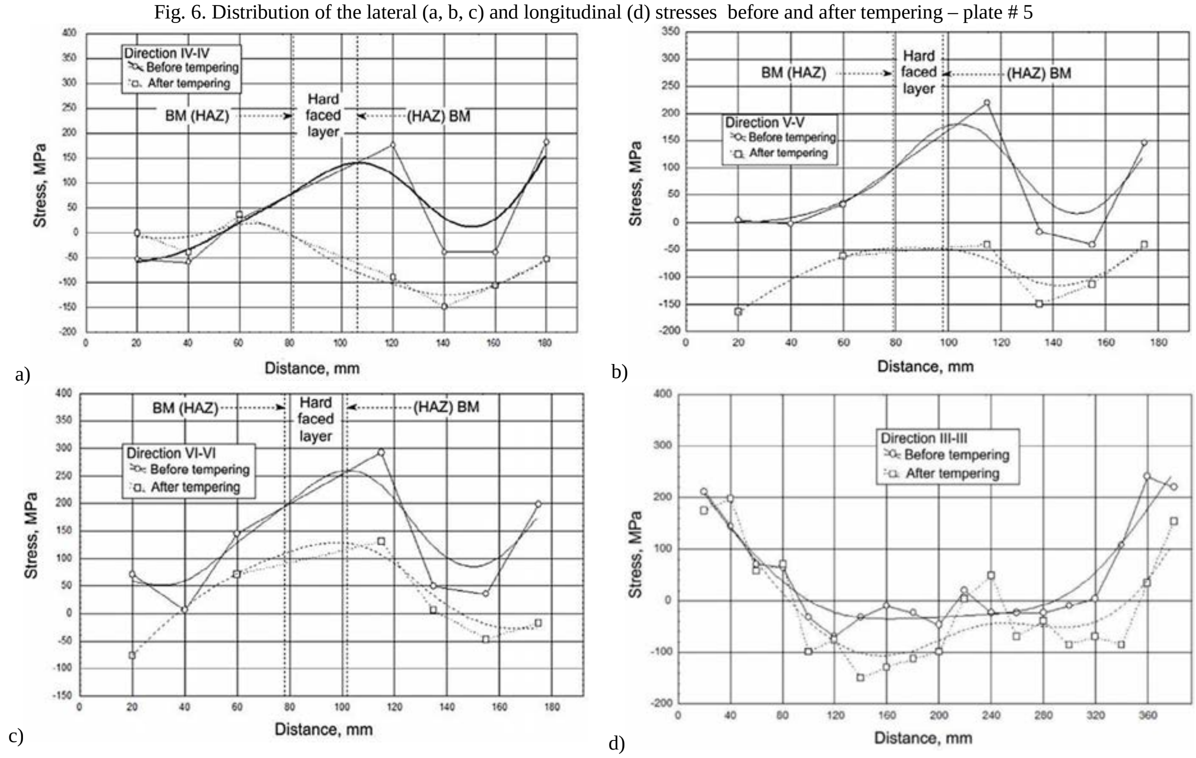

Fig. 7. Distribution of the lateral (a, b, c) and longitudinal (d) stresses before and after tempering – plate # 6

- The high tempering is more favorable for the thick – more massive plates (or parts) and multi-layer hard-facing, while the medium or low tempering is recommended for the thinner plates (parts) and single-layer hard-facing. This means that the proposed ("optimal") tempering regime should be modified, both with respect to T_{max} and with respect to time of keeping at that temperature (Fig. 5d);

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