

## **COMPARATIVE STUDY OF RESIDUAL STRESS STATE INDUCED BY QUENCHING AND TEMPERING**

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### **ABSTRACT**

In the present study the residual stress state and macroscopic deformation of automotive rack bar semi products were examined after induction and conventional quenching and tempering. Induction hardening and tempering were carried out in the production line while the conventional treatments were performed in laboratory. Nondestructive residual stress mappings were performed after quenching and tempering on the same rods. The macroscopic deformation was also monitored. It was experimentally shown that the induction treatment produced a more convenient stress state and the tempering initiated the stress relaxation, but the non-uniform longitudinal stress distribution formed during quenching still remained.

### **INTRODUCTION**

It is well known that residual stress is introduced within solid materials during many types of processing methods including heat treatments, machining, grinding, casting, etc. [1]. The type and magnitude of the stress state induced by such methods can be extremely various depending on the type and conditions of the treatment and geometry of the sample. The presence of residual stress can either be harmful or useful. If undesired residual stress is arisen within a machine component during its manufacturing steps, it can lead to deformation. Since the geometry of automotive components must be kept strictly within tolerances, more and more attention is given to the importance of residual stress in the field of automotive industry. Residual stress state induced by hardening (quenching and tempering) can be more complex due to complex dilatations associated the heating, cooling rate and the phase transformations [2-5].

In the present paper a comparative study on residual stress states of induction hardened and conventional hardened cylindrical bars was performed. The correlation between the applied heating and cooling methods, the eccentricity and the formed stress asymmetry was investigated. The effect of tempering is also numerically presented. Additional result associated with micro stress relaxation and solid phase reactions are also presented.

### **EXPERIMENTAL**

The induction heat treatment (quenching and tempering) were carried out of the examined rack bar rods produced from 37CrS4 type steel in a continuous process line by Lech-Stahl Veredelung GmbH, in Oberndorf am Lech, Germany. The quenching and the subsequent tempering temperature were 880°C and 720°C, respectively. 500 mm rods with diameter (D) of 26 mm were cut for the examinations. The conventional hardening was carried out on 42CrMo4 type steel rods with a resistance heating furnace set to 850°C, followed by quenching in 5% polymer solution in the Institute of Physical Metallurgy, Metalforming and Nanotechnology, University of Miskolc. During quenching, the rod was sunk into the cooling media in horizontal position. The lengths and the diameter of rod were 190 mm and 20 mm respectively. Table 1 shows the chemical composition of the examined steels.

Table 1. The chemical composition of the examined steels, w%

steel	C	Si	Mn	Cr	Mo	S
42CrMo4	0,42	0,25	0,75	1,1	0,22	<0,035
37CrS4	0,37	0,25	0,70	1,05	-	0,02-0,04

After the heat treatments, a mesh was created on the rods containing eight generatrix (1-8, A-H). 5 and 7 measured points were used on each generatrix on the induction hardened and conventionally hardened rods, respectively. 25 measured points were used on one generatrix in our previous work on the same length of induction hardened rods which showed homogenous stress state along the longitudinal axis, therefore the number of measurement points was decreased.

The macroscopic deformation of the conventionally hardened sample was determined by eccentricity measurement and 3D topography methods. An ATOS optical system at the Alcoa Forgings and Extrusions Firth Rixson Hungária Kft was used to determine the 3D deviation from an etalon sample with the same geometry.

Afterwards, non-destructive (sampling free) X-ray diffraction based residual stress mapping was performed on the rods at the Institute of Physical Metallurgy, Metalforming and Nanotechnology of the University of Miskolc with a Stresstech Xstress 3000 G3R X-ray diffractometer using Cr K $\alpha$  radiation. The stress was calculated from the shift of the {211} reflection of ferrite according to the  $\sin^2\psi$  method using Young's modulus (E) 210000 MPa and Poisson's ratio of 0.29. Reflections were obtained in  $\psi$  geometry from 3 tilting positions in the  $-45^\circ/+45^\circ$  range according to Fig. 1 The spot size was 3 or 4 mm in diameter. The stress was measured with less error (scatter) than  $\pm 50$  MPa in every point.

## RESULTS

After the quenching, a notable macroscopic distortion was measured on the conventionally hardened rod. Table 2 shows the eccentricity determined by tracer finger, while the Fig. 2 shows the colored topography map according to the size deviance. The biggest difference was found between the 1st and 8th generatrix which was the part of the rod that was sank into the liquid last. It is also interesting that the last measurement point (at 140 mm) shows the largest eccentricity value. The deviances in the 3D map are in the same part of the rod even if the values differ,

which is caused by the disturbing effect of the surface roughness. The advantage of the 3D topography is that we get information about the whole surface.

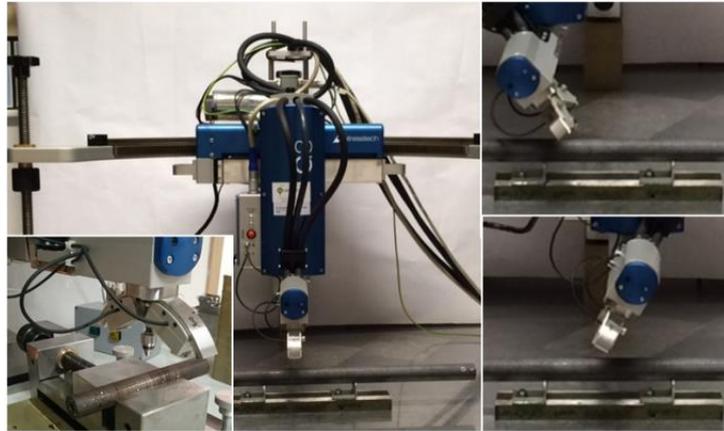


Fig. 1. Residual stress measurement of induction and conventionally hardened rods using modified  $\sin^2\psi$  method.

Table 2. The eccentricity of conventionally quenched rod

	Distance from the end face		
	20 mm	80 mm	140mm
eccentricity between the 1 <sup>st</sup> and 8 <sup>th</sup> generatrix	0,00mm	0,04 mm	0,09 mm

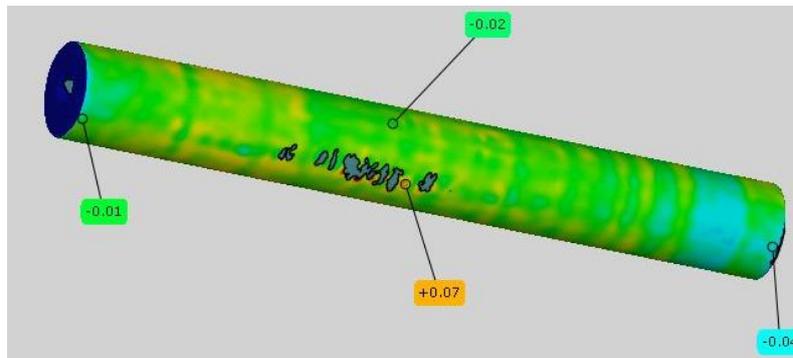


Fig.2. 3D topography of the examined rod obtained with ATOS optical system after quenched 5% polymer solution

The next figures represent the residual normal stress map on the surface along the generatrix. All of the recorded data were measured in the longitudinal direction. Figs. 3 and 4 show the result of the conventionally quenched rod and the results of the same rod after tempering. The stress distribution after quenching is very similar along the generatrix (lines) but a strongly non-uniform longitudinal stress

distribution can be observed. The values of stress data are very significant. The maximum eccentricity part holds 500 MPa tensile stress, which is close to the yield stress of this type of steel. After tempering, the non-uniform stress distribution still remained, but the stress values are decreased by one magnitude. The decrease in the compression side was smaller.

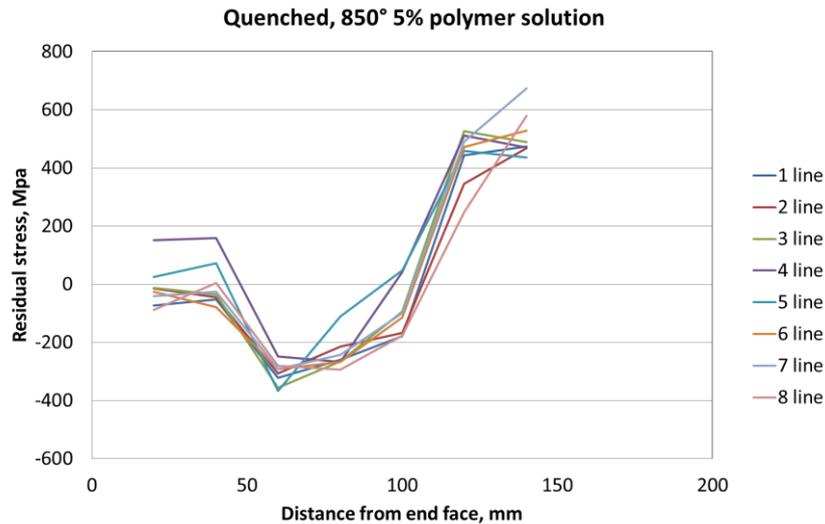


Fig.3. Residual stress data on the surface along the 8 generatrix after conventional quenching

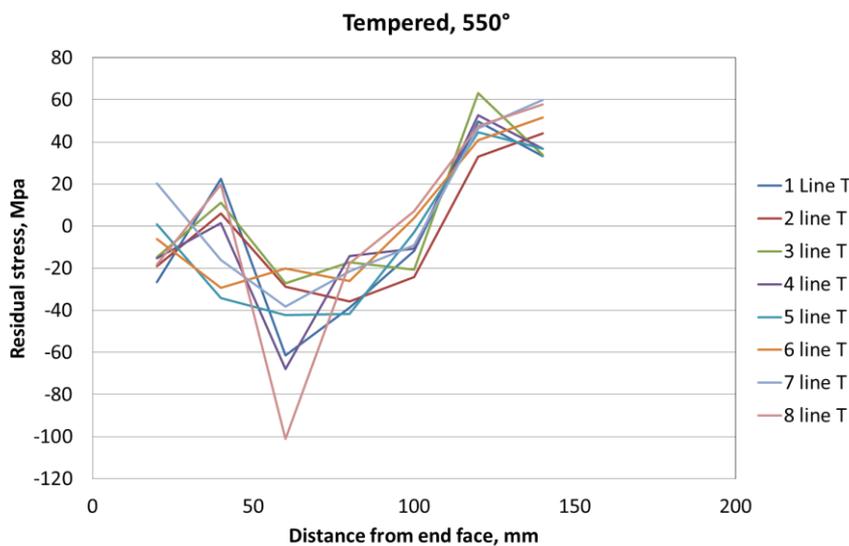


Fig.4. Residual stress data on the surface along the 8 generatrix after conventional quenching and tempering

The same results for the induction hardened rods are shown in Figs. 5 and 6. The small amount of residual stress after induction hardening is remarkable. This can be one of the biggest benefits of this method. The tempering further decreases the stress values.

Due to the X ray diffraction method not only the macroscopic stress state, but other parameters of the interference function (ferrite {211}) can be determined such as

full width at half maximum value (FWHM), which is correlated with the microscopic stresses (besides dislocation density, grain size and composition inhomogeneity) Furthermore, some solid state reactions, such as carbide precipitation can be monitored through the shift of the Bragg angle. Figs. 7 and 8 present the FWHM data for the two rods hardened with different methods. It was seen that the macroscopic stress state was notably larger after conventional quenching than after induction hardening. Similarly, in case of induction hardening, smaller FWHM values were measured, which refers smaller microscopic stresses, and smaller dislocation density. Tempering, of course further decreased the micro stresses and dislocation density for both quenching methods, which is seen on the decreased FWHM values of both tempered rods.

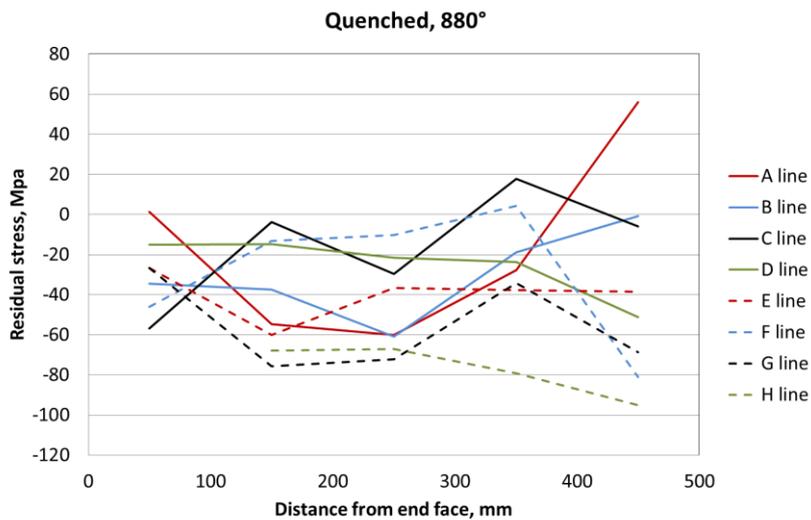


Fig.5. Residual stress data on the surface along the 8 generatrix after induction quenching

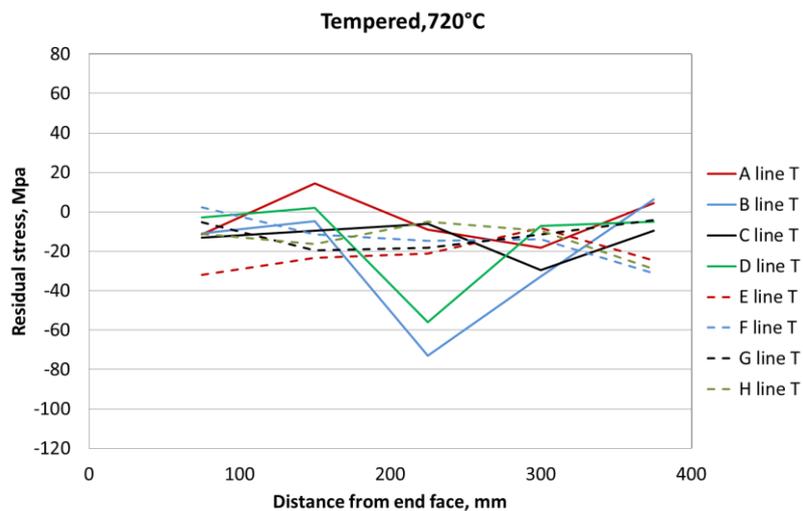


Fig.6. Residual stress data on the surface along the 8 generatrix after induction quenching and tempering

The shift of Bragg angle can be seen in Figs. 9 and 10 in case of conventionally and induction hardened rods. Because the very similar concentration of the examined steels, the tempered martenzites (ferrite) gave the same Bragg angle but the quenched martenzites show a difference in Bragg angles which means a difference in concentration, and, consequently, different hardness and/or toughness of the two quenched rods.

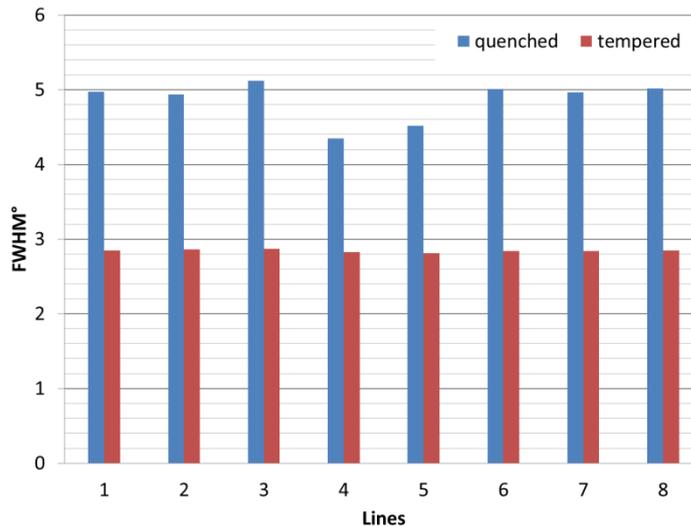


Fig.7. Line by line average FWHM data of the conventionally treated rod

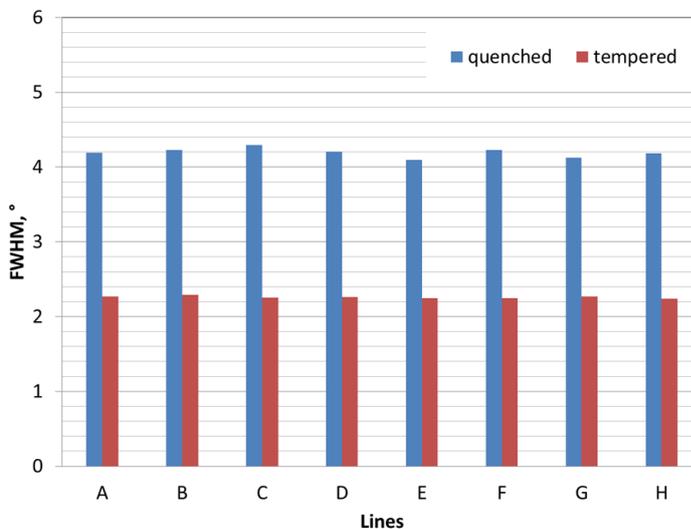


Fig.8. Line by line average FWHM data of the induction hardened rod

## SUMMARY

Based on the nondestructive X ray diffraction residual stress measurements performed on rack bar semi products, it was experimentally showed that:

- the induction hardening left a favorable stress state compared to conventionally quench bar,
- the longitudinal stress distribution, the macroscopic deformation and the position of the rod during the immersion into the quenching media were in good agreement for the conventionally quenched bar,

- tempering decreased the stress values in macro and micro scale as well but the non-uniform longitudinal stress distribution remained unchanged,
- the presence and direction of macroscopic eccentricity could unambiguously be connected to the stress state of the rod, and the presence of eccentricity do not necessarily mean a stress-free, relaxed state.

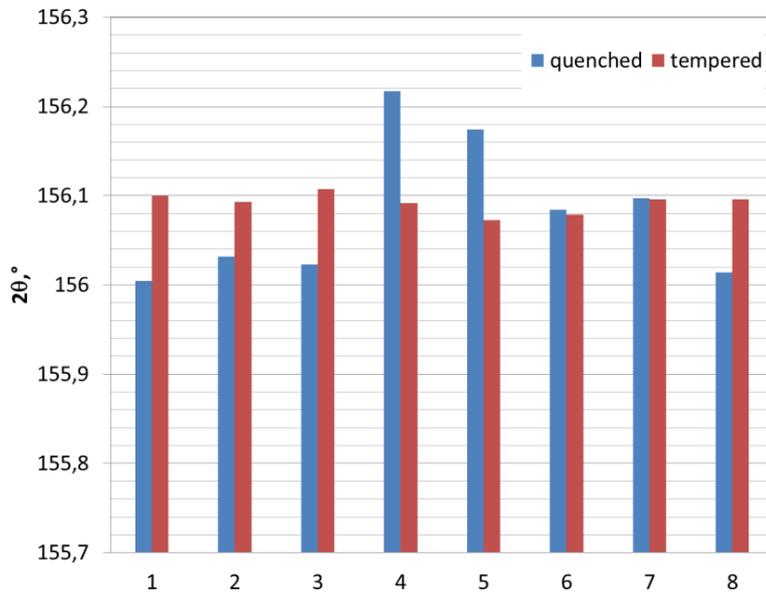


Fig.9. Line by line average Bragg angle data of the conventionally treated rod

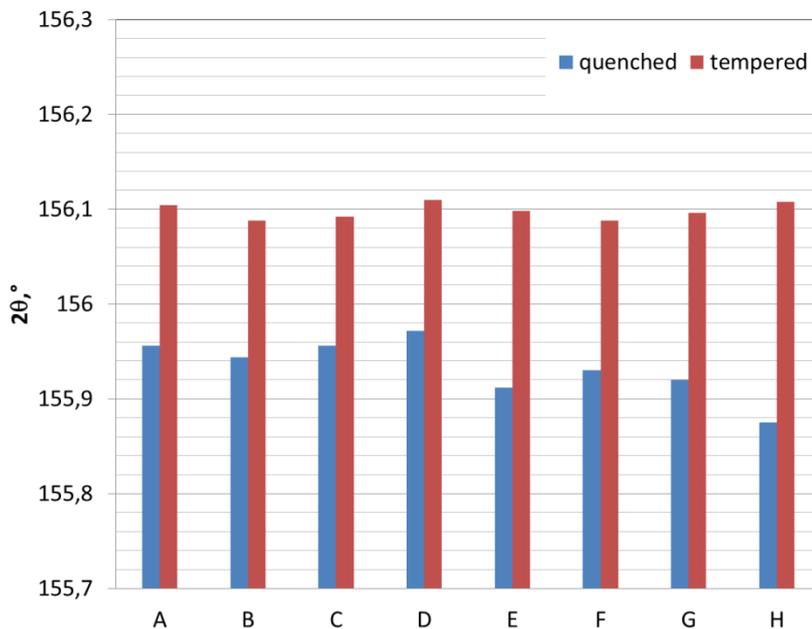


Fig.10. Line by line average Bragg angle data of the induction hardened rod

## ACKNOWLEDGEMENTS

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