Numerical Simulation of Induction Hardening of Torsion Bar

H. Norouznejad, G.H. Farrahi

Abstract—**In order to improve the fatigue performance of torsion bar, induction surface hardening is performed. The aim of the present study is to compare the experimental residual stress fields measured by X-ray diffraction with those predicted from finite element modeling of the whole induction surface hardening process. Temperature and residual stress distributions are affected by the component geometry, the material behavior and the induction treatment parameters. Based on the residual stress distribution and the fatigue loading, cracks can nucleate from the surface or below the hardened layer. Therefore, it is very important to determine the residual stress distribution and optimize the process, especially for safety critical engineering components. Results of present study show that the improvement of fatigue performance is due to development of both hard microstructure and compressive residual stress at the surface layer of torsion bar during induction hardening.**

Index Terms—**Induction Surface Hardening, Residual Stress, Finite Element Method, Torsion Bar.**

I. Introduction

Unlike the other types of springs, torsion bars are simple rods which are made in a variety of dimensions and for different applications. They are used in some types of automotive rear suspension systems which give coiled-spring-like performance based on the resistance to twisting properties of steel. As the suspension moves, the bar twists along its axis providing the springing motion. Working mechanism is based on the use of steel in the elastic range. Torsion bars tolerate cyclic torsion loads. Therefore, in order to increase the elastic limit and fatigue life, different metallurgical considerations such as material selection and manufacturing process should be investigated precisely. In order to increase the fatigue life, induction hardening is an attractive option. Induction hardening is the heating process of conductive materials utilizing the principle of electromagnetic induction, in which eddy currents are generated within the metal. It is increasingly used in automotive industry, because of offering a number of advantages over the other types of heat treatment methods, such as low surface oxidation, small distortion, and good possibilities for automation. It is especially suitable for axisymmetric parts. It offers two major effects which results in improving fatigue performance. After induction hardening the core of workpiece is tough and the surface is hard. Furthermore, it induces compressive residual stresses to the surface. This configuration has proved to be very effective in extending the fatigue life, i.e. delaying fatigue crack initiation [1]. Major part of eddy current is concentrated at the outer layer of workpiece which is considered the hardened layer. By quenching the component in water or oil, the surface layer is altered to form a martensitic structure which is harder than the base metal.

During cooling and heating processes, ongoing changes occur in the stress field. If at any point of the workpiece local stress exceeds the yield stress in that temperature, a uniform plastic flow is generated which results in residual stress. In general, creating compressive residual stress is the desired condition that enhances fatigue life. Modeling of this process is complex because of interaction of non-stationary electromagnetic and temperature fields that is accompanied by metallurgical changes in hardened material dependent on the history of heating and cooling [2]. Since experimental methods of measuring residual stresses like X-ray diffraction are difficult and expensive, simulation of heat treatment processes have been widespread in order to calculate residual stresses. Numerical analysis of thermal residual stresses resulting from quenching of steels has been studied for years, and a relatively large number of works have been reported. In contrast, there are a few studies about residual stresses resulting from induction surface hardening. Zhonghua et al. [3] proposed a set of simple formulae in order to predict the residual stresses induced by induction hardening. In the present study, in addition to simulation of induction hardening process and calculation of residual stresses using finite element method, influence of this process to increase the fatigue life was investigated. The results presented as temperature history and residual stress distribution, are in good agreement with experimental measurements.

II. Finite Element Model

The generated current flows predominantly in the surface layer and the depth of this layer being dictated by the frequency of the alternating field, the surface power density, the permeability of the material, the heat time, and the diameter of the bar or material thickness. The layer is heated in the austenitic temperature and then is cooled by water flow which is sprayed on the workpiece surface.

Three-dimension geometry is simplified to two-dimension, using axisymmetric conditions. As can be seen

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in Fig. 1 the 2-D model has three regions, (i) coil, (ii) workpiece, and (iii) air, which have different temperature dependant material properties. The model is axisymmetric about the Y axis.

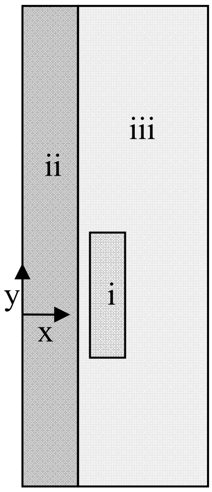

Fig. 1. Regions of model (i) coil, (ii) workpiece, and (iii) air.

The material obeys the Von-Mises plasticity criterion which modeled by an isotropic thermal elasto-plastic law. The total strain is considered as a sum of: (i) an elastic strain, (ii) a plastic strain, (iii) phase transformation plasticity, and (iv) a thermal strain. Transformation plasticity is a significantly increased plasticity during a phase change. Therefore the prediction of residual stresses due to the solid phase transformations is incomplete without the consideration of the significant contribution of this additional strain [4]. It is generally considered as the anomalous plastic strain observed when metallurgical transformation of steel (austenite to martensite) occurs under an external applied stress even much lower than the yield stress of the weaker phase [5] which has been taken into account in the present study. Coefficient of thermal expansion includes both the temperature-induced and the transformation-induced strains. Thus, negative values of α are considered, which refer to expansion during phase transformation, despite decreasing temperature.

First, temperature history of all nodes during heating process is calculated, solving electromagnetic-thermal problem. Then, using this temperature history, stresses of heating process are obtained, performing a structural analysis. Next, temperature history of cooling process is calculated solving the problem of heat transfer from the workpiece to sprayed water. In this stage, first, calculated stresses of heating process are applied to the model as prestress, then, employing temperature history of cooling process, a transient thermal-structure analysis is done. The results are residual stresses arising from heating and cooling processes during induction hardening.

Fig. 2 shows the algorithm used in this work for simulation of induction hardening. Latent heat of phase transformation was neglected because it has no significant effect on the residual stresses [3].

The material of investigated torsion bar is 55Cr3 (SAE 5155), a low alloyed carbon steel whose chemical composition is given in table I.

TABLE I
CHEMICAL COMPOSITION OF 55Cr3

C	Mn	Cr	Si
0.57	0.85	0.8	0.3

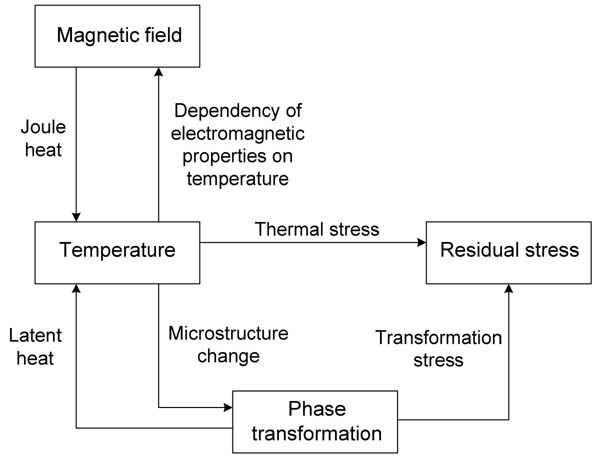

Fig. 2. Algorithm of simulation

III. Verification

In order to validate our presented model, the results are compared with the published results of Zhonghua et al [3] measured by X-ray diffraction. Experimental results of axial residual stresses and those obtained in this study are shown in Fig. 3. It is seen that there is a good agreement between the two sets of results, especially at the surface layer.

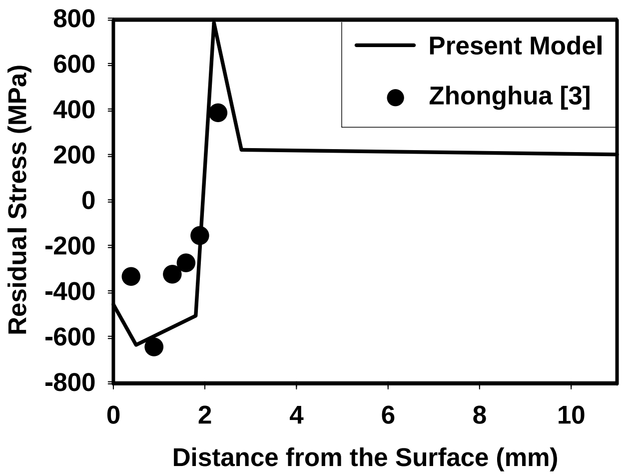

Fig. 3. Verification of the presented model.

Residual stresses at the surface layer are compressive and below the hardened layer are tensile.

IV. Result and Discussion

A. Temperature History and Microstructure

Fig 4 shows temperature history of core and surface of the torsion bar. During the heating process while the temperature of the surface increases sharply to about 1100 ºC; the temperature of the core increases gradually. The moving velocity and the length of coil are 610 mm/s and 15 mm, respectively. Based on these dimensions it is calculated that the surface of workpiece experienced a high heating rate of 700 ^{o}C/s. While this heating rate is achieved by electromagnetic induction, the core of workpiece is heated only by heat conduction from the surface layer toward the lower layers. Because of the direct contact between quenching water and the surface, temperature of surface decreases sharply during cooling process.

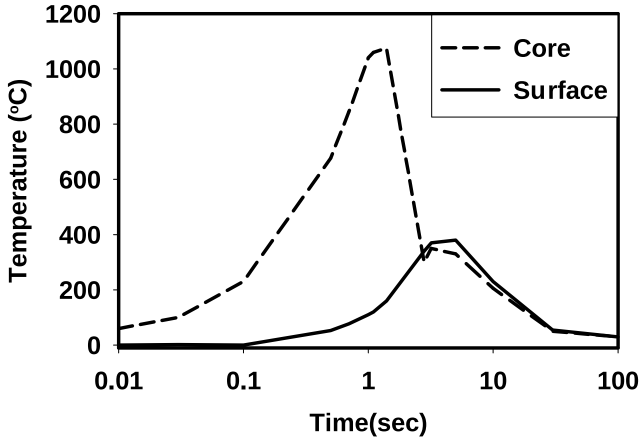

Fig. 4. Temperature history of core and surface.

Fig. 5 shows the variations of temperature from the surface toward the core after different heating times. Since the austenitizing temperature is around 780 ^{o}C , about 2 mm of surface is subjected to phase transformation. Frequency of induction is 9.5 kHz.

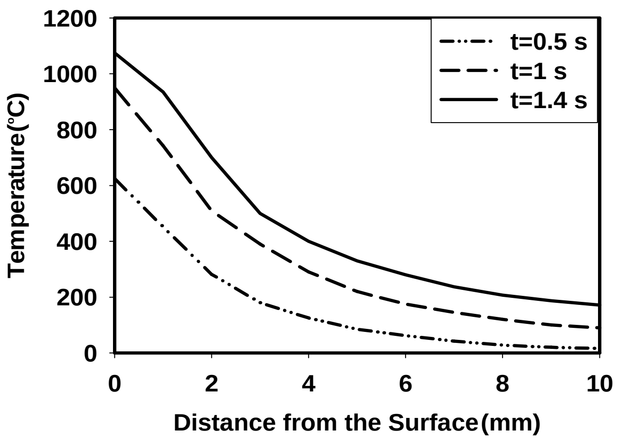

Fig. 5. Time variation of through-thickness temperature during heating.

Fig 6 shows temperature changes from the surface to the core during the cooling process. Due to high cooling rate near the surface, almost the entire austenitized layer transforms to martensite.

Microstructures of material at the surface layer of workpiece before and after induction hardening are shown in Fig. 7. The material microstructure before the process consists of ferrite and pearlite, but the microstructure of the hardened layer after the process is almost fully martensite.

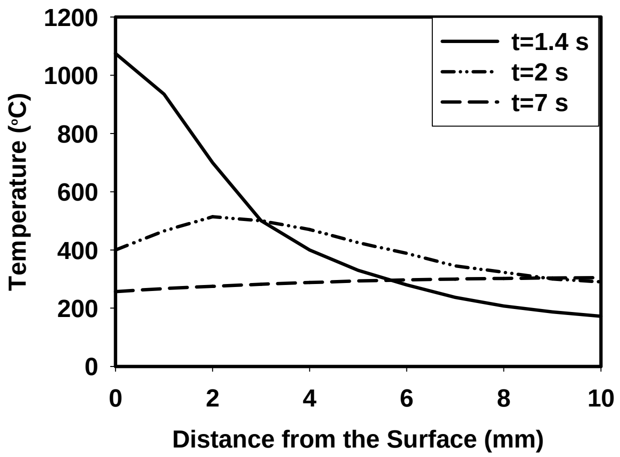

Fig. 6. Time variation of through-thickness temperature during cooling

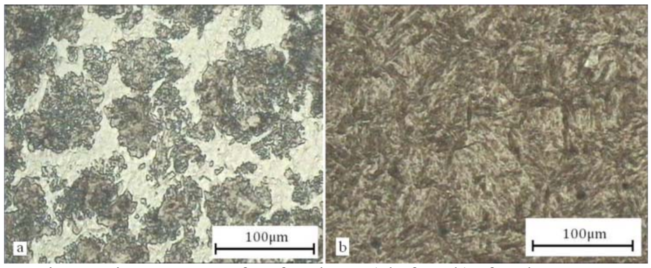

Fig. 7. Microstructure of surface layer a) before, b) after the process

B. *Residual Stresses*

The length and diameter of investigated torsion bar are 1035 and 20 mm, respectively, and the flow rate of water sprayed onto torsion bar during the induction process is 16 lit/min.

Fig. 8 shows the simulated residual stresses of induction hardening. Although hoop and axial residual stresses are slightly different, the trends are alike. Location of maximum compressive residual stress is below the surface.

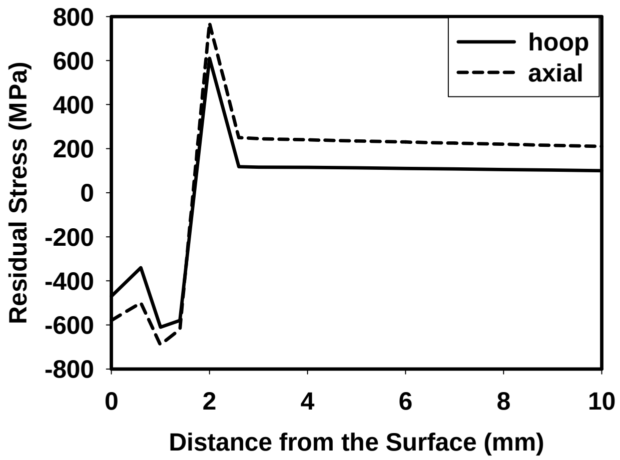

Fig. 8. Simulated residual stresses

There is a very considerable change in residual stress magnitude below the surface. This region is the boundary of phase change from induced martensite to initial ferrite-pearlite.

C. Simulation of Fatigue Test

In order to investigate the effect of induction hardening on improvement of fatigue performance in torsion bar, a standard fatigue test is simulated using finite element method.

The offered procedure for fatigue test of investigated torsion bar by manufacturer is 300,000 cycles in the twisting angle of 22 degrees. The test is performed in a completely reversed loading.

In order to determine the influence of residual stresses on fatigue performance, the empirical relation (1) was used [6]

$$\sigma'_w = \sigma_w - m\sigma_{res} \quad (1)$$

where σ_w is the fatigue limit of a completely reversed loading, σ_{res} is residual stress which is known to be equivalent to mean stress, and the constant *m* which describes the dependency of fatigue strength on mean stress, increases from 0.2 to 0.6 with the hardness of material as is shown in Fig. 9 [6]. It is clear that residual stress is more effective for harder material.

The surface hardnesses of material before and after the hardening process were 302 and 674 HV, respectively.

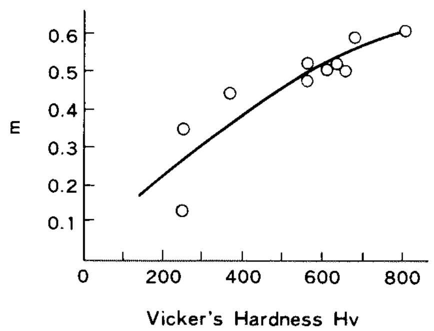

Fig. 9. Constant *m* [6]

The cumulative fatigue damage calculated from the fatigue test results, are shown in table II. The development of compressive residual stresses and martensite microstructure on the surface has significant effects on the improvement of fatigue life.

TABLE II
RESULTING CUMULATIVE FATIGUE

workpiece condition	cumulative fatigue damage
before induction process	6.01
residual stress	1.54
residual stress & martensite	0.44

V. Conclusion

Finite element modeling of induction hardening for a torsion bar was carried out. Temperature history and residual stress distribution of workpiece were calculated. From this work, the following conclusions can be made:

- Good agreement between experimental measurements and simulated results proves that simulation of process is more practical in most of the applications.
- The surface layer of workpiece experienced high heating rate, because of concentration of eddy current on the surface, and also high cooling rate, because of large convection coefficient.
- Due to high cooling rates, the austenitized surface layer transformed to martensite entirely.
- Hoop and axial residual stresses at the hardened layer are compressive which are beneficial with respect to fatigue performance.
- Maximum compressive residual stress is located below the surface.
- Simulated residual stresses around the boundary of ferrite-pearlite and martensite phases shows a great change from tensile to compressive residual stress which could be the region of crack nucleation.
- In addition to compressive residual stresses, phase transformation of hardened layer to martensite has a significant effect on improvement of fatigue life.

References

[1] D. Coupard, T. Palin-luc, P. Bristiel, V. Ji, C. Dumas, "Residual stresses in surface induction hardening of steels: Comparison between experiment and simulation," *Materials Science and Engineering, 2008, pp. 328-339.*

[2] J. Barglik, I. Dolezel, P. Karban, I. Kwiecen, and B. Ulrych, "Comparison of Two Ways of Induction Hardening of Long Steel Tubes," *Int. Symposium on Theoretical Electrical Eng. 2005.*

[3] X. Donghui, L. Zhonghua, and L. Jingxie, "Expressions for predicting the residual stress in surface," *Modeling and Simulation in Materials Science and Engineering, 1996, pp. 111-122.*

[4] R. K. Janutiene, J. Zvinys, "Experimental analysis of transformation plasticity and stress relaxation of carbon spring steel during tempering," *MECHANIKA, 2008, pp. 77-80.*

[5] V. Runser, J. Hoffmeister, and V. Schulze, "Model for the solid state phase transformation and transformation plasticity during casting in grey cast iron GJL350," *15th International Conference on the Strength of Materials (ICSMA-15), 2010.*

[6] K. Kiobuchi, T. Hayama, and S. Kawai, "Residual stress and fatigue strength of surface hardened-components," *First Conf. Int. sur le Grenaillege de Precontrainte (Paris), Pergamon Press, Oxford, 1981, pp. 413-419.*