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Residual stresses after deep rolling of a torsion bar made from high strength steel

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ABSTRACT

In this article, the process of deep rolling of the torsion bar for heavy armored vehicles is investigated. Deep rolling is a mechanical process of introducing compressive stresses into near surface regions of the working piece. The main objective of deep rolling of the torsion bar is to increase fatigue strength and life time of the torsion bar. The investigated specimen (quenched and tempered before deep rolling) was deep rolled according to the producer's standard technology procedure. The material used in this study was the TORKA steel, which is a low-alloy steel with high strength and toughness. The material was characterized through a series of monotonic and cyclic tension compression experiments. Parameters used in the process were changed during deep rolling of the specimen and their influence was measured. Residual stresses resulting from the deep rolling process were measured with an X-ray diffraction (XRD) device and evaluated with the use of commercial finite element method software. An isotropic and kinematic hardening material model based on the cyclic characteristics of the material was used in three dimensional simulation of deep rolling. Numerical simulation results agree very well with the results obtained from XRD measurements.

1. Introduction

Mechanical surface treatment processes commonly used today may be roughly divided into cutting and non-cutting methods (Schulze, 2006). Deep rolling is a process of mechanical surface treatment which includes relative movement of the deep rolling tool – roller. The objective of deep rolling is to introduce work hardening and compressive residual stresses into near-surface regions in order to increase fatigue strength. Residual stresses are caused by a high value of external load that exceeds the yield strength of a material within subsurface region. Consequently, deformations occur, creating residual stresses and the associated microstructural work hardening or work softening effects. The value of residual stresses depends on many process parameters such as rolling force amplitude, contact geometry, friction coefficient and feed rate of the rollers. For the same reason, deep rolling is used in the production of torsion bars. A torsion bar is a geometrically simple mechanical part which twists under the load of a vertically moving wheel. As the highest shear stresses present on the surface of torsion bar, surface damage control has a major impact on durability of the torsion bar. The major mechanical surface processes used in the production of torsion bars are shot peening and deep rolling (Van Eerden et al., 2000). The residual stresses after deep rolling extend noticeably deeper into the interior of the material than the residual stresses do after shot peening (Schulze, 2006). For example, higher rolling force will produce higher and deeper residual stresses in the longitudinal and circumferential direction (Altenberger, 2005) and higher friction coefficient will cause higher tangential forces and circumferential residual stresses (Schulze, 2006). Because many process parameters influence the residual stress field, the FE modeling is the only way to accurately define residual stresses after deep rolling. The objectives of this paper are to build an accurate FE model of deep rolling that can be used in further analysis and to verify the FE model with the measured values of residual stresses.

2. Survey of previous work

Extensive literature has been published on residual stresses after mechanical surface treatment, but only a few publications deal with residual stresses after deep rolling and FE simulation of the deep rolling process. One of the first published articles that described FE simulation of deep rolled component was published

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by Guagliano and Vergani (1995). Their paper discusses the influence of the deep rolling force in the evolution of residual stresses in notched components. The material model used in this simulation is a simple isotropic hardening model, the roller is modeled as a rigid body and the friction is neglected. Simulations by Liebisch, Jung, Achmus have been set as two dimensional, solved in an implicit code (first presented case) and three dimensional contact problem with elasto-plastic workpiece with isotropic material hardening (second and third presented case) (Schulze, 2006). The friction was neglected in order to reduce the calculation time. In the second case, the roller was assumed as an elastic body, and in the third case, the roller was simulated as a rigid body. It was shown that the roller may be assumed to be rigid, without skewing the residual stresses state. Explicit Abaqus model was presented by Mayer et al. (2000). The results reveal that an increase of the rolling force leads to an increase in the amount and the depth of the compressive stresses. Simulation of a similar process of roller burnishing was presented by Yen et al. (2005). A comparison between 2D and 3D simulation of the burnishing process was established. Authors concluded that the 2D model predicts residual stresses better than the 3D model. The 3D model tends to predict the maximum compressive stresses at shallower depths due to the boundary effect and the undersized workpiece in the thickness direction. Data on importance of the right material model and influence of kinematic hardening on residual stresses was published by Demurger et al. (2006). The simulation of residual stresses after deep rolling was based on a nonlinear kinematic hardening model. The simulation and the comparison of shoot peening with deep rolling were presented by Majzoobi et al. (2009). They used the Johnson–Cook constitutive material model, the roller was assumed as a rigid body, and the static friction coefficient was 0.4 and 0.6. A combined isotropic/hardening model was implemented in the FE simulation done by Bäcker et al. (2010). This paper examined the influence of different parameters of deep rolling on the residual stresses. They presented a deep rolling modeling with the coupled FE method and boundary element method. In the simulation of ultrasonic surface rolling process (Liu et al., 2011), authors implemented a nonlinear combined isotropic kinematic hardening model, the Coulomb friction coefficient was 0.2. One of the studies simulates the influence and evaluation of deep rolling parameters on residual stresses by explicit dynamic algorithm (Manouchehrifar and Alasvand, 2012). They used the Johnson Cook material model. Simulation of roller burnishing was done by Balland et al. (2013). Authors used an isotropic hardening material model based on Rastegaev type geometry compression tests. They used a set of connector elements to transfer the rolling force from the roller to the workpiece. A combined isotropic and kinematic hardening model was used in simulation done by Trauth et al. (2013). They also used multi-point connectors for modeling the kinematic system of deep rolling. The friction was modeled using an extended version of the standard Coulomb friction model, considering stick–slip effects, which can occur during deep rolling at high pressures. The FE model was verified with experimentally measured stresses. Residual stresses obtained by FE simulation were compared with the results obtained by the developed method of the similarity mechanics approach.

3. Experimental setup

The investigated specimen was made from the TORKA-ESR steel (Metal Ravne designation). This type of steel is used for serial production of torsion bars and it was specially developed for this kind of application. Nominal chemical composition of the steel is given in Table 1. AISI 4340 has a similar chemical composition.

Table 1
Chemical composition (in wt%) of the Torka steel (Metal Ravne designation).

	C	Si	Mn	Ni	Cr	Mo	V	Cu	S	P
Min.	0.42	0.17	0.5	1.3	0.8	0.2	0.1	0	0	0
Max.	0.5	0.37	0.8	1.8	1.1	0.3	0.18	0.25	0.001	0.02

The investigated specimen was quenched and tempered with a batch of torsion bars. The diameter and the length of the investigated specimen are equal to the diameter and the length of the main body of the torsion bars. Specimen and torsion bars were hardened according to a typical technology procedure to the required hardness level of 54 ± 1 HRC. Control cylinders were used for the control of heat treatment process and cyclic characterization of the material. The specimen nominal dimension was Φ61.7 mm × 1750 mm. The specimen was polished prior to deep rolling.

The specimen was deep rolled using a purpose-built machine. The carriage with rollers and the position of the specimen is schematically shown in Fig. 1. Three rollers, hydraulically controlled, are placed at a 120° angle around the workpiece. The specimen is fixed in the chuck at one end and supported by a movable tailstock spindle on the other end. The pressure at the rollers is regulated by a central oil valve and distributor. The feed rate is regulated through the longitudinal movement of the carriage with rollers.

The process of deep rolling is done in three steps. First, rollers are pressed against the rotating workpiece. When the requested pressure is reached, the carriage with rollers moves in the axial direction with the requested feed rate. At the end of the deep rolled area, rollers are moved away from the workpiece. During deep rolling, the specimen is cooled and oiled with the highly refined mineral oil, enhanced with sulphur/phosphorus extreme pressure additive technology. The deep rolling force is calculated from the pressure in roller cylinders. The feed rate of deep rolling was recorded from the machine and controlled with measurement of the distance through time.

The process parameters were adjusted to the existing parameters that are used in the production of torsion bars. The specimen was divided into several measuring fields which were rolled with different process parameters. Each measuring subfield was rolled for a length of 100 mm. To avoid the influence of processing parameters from one rolled area to another, non-rolled gaps with a length of 20 mm and 40 mm were placed between the rolled areas. Overall there were three major measuring fields, rolled with same rolling pressure. Each major measuring field consists of three different measuring subfields which were rolled with different feed rate. Hardness, roughness and residual stresses were measured in each measuring subfield at two opposite points. There are eighteen different measuring points on the surface of the deep rolled specimen (Fig. 2).

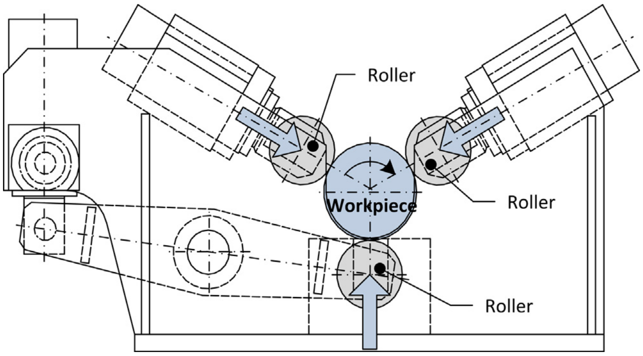

Fig. 1. Schematic view of the deep rolling machine.