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Finite element approach toward an advanced understanding of deep rolling induced residual stresses, and an application to railway axles

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ABSTRACT

A full-scale railway axle, made of medium strength steel EA4T and adopted for high-speed applications, is deep rolled. The induced residual stresses were experimentally characterized by X-ray diffraction and hole drilling. A realistic finite element model is proposed to overcome some of the existing shortcomings in simulation of deep rolling. Deep rolling coverage is defined, formulated and incorporated into the simulation. The model is validated by the experimental measurements. A parametric study is performed to investigate the effect of rolling force (4–19 kN), rolling feed (0.1–0.7 mm/rev) and roll geometry (1.5–10 mm roll tip radius) on the distribution of residual stresses and the induced hardening. A fatigue crack propagation algorithm is used to analyze the influence of the technological parameters on the lifetime of railway axles. Lower feeds, higher loads and thicker rolls, all resulting in higher coverage, can result in higher improvement against fatigue crack propagation. However, extremely high coverage can deteriorate the performance of deep rolled components. Coverage can effectively serve as a master parameter in deep rolling. As a general rule of thumb, adopting deep rolling feed to get a coverage level of 500–900%, while avoiding too high rolling loads and too thin rolls, can induce a suitable compressive residual stress distribution; and effectively prevent/retard fatigue crack propagation.

1. Introduction

Deep rolling is a surface treatment where roll or ball-point tools are used to press the target surface. As the roll sweeps the surface, the latter is plastically deformed and a groove is created. The elastic recovery of material, surrounding the plastic zone, produces compressive residual stresses in the surface layers. Deep rolling should be distinguished from roller burnishing, which mostly aims to enhance surface roughness quality by applying much lower forces. Indeed, deep rolling is aimed to extend component's fatigue life by generating compressive residual stresses. Deep rolling is applied on crankshafts, valve shafts, screws, bore-holes, axles, bolts and threaded parts in automotive industries, general mechanical engineering and, to a certain extent, in aerospace industries [1].

Large depth of the affected layer, exhibiting sufficient work hardening and compressive residual stresses, as well as generation of glossy surfaces with low roughness is the advantage of deep rolling with respect to other surface treatments [2]. For instance, the typical depth of the compressed layer in shot peening or nitriding is a few hundred micrometers [3,4] while deep rolling is able to extend the compressed layers more than 1 mm deep [5].

Rolling force or pressure, rolling feed, roll geometry, material, contact conditions and number of overruns are the important factors of a deep rolling treatment. Among them, force or pressure is believed the most influential one [2]. Only optimized rolling forces could increase the fatigue strength of deep rolled components; as too low rolling forces have no pronounced effect on the fatigue strength and too high forces might be even detrimental by inducing micro-cracks.

A large body of experimental research to characterize microstructure [6], cyclic deformation [7,8], fatigue [6,9–11], fretting [12], wear [13], thermal stability [14] and residual stress relaxation [15–17] of deep rolled components is available in the literature. However, a thorough analysis of the residual stress itself, as one of the most important outcomes of the process, is somewhat missing. Quantitative description of deep rolling usually aims to obtain residual stress distribution. Nonlinearities arisen from material behavior, surface conditions and large displacements limit the application of analytical approaches. Finite element analysis could be an effective alternative to overcome such complexities. A few attempts have been made for the similar treatment of fillet rolling. Chien et al. [18] simulated residual stress distributions using a 2D

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plane strain elastic–plastic finite element analysis. Rolling depth of the fillet surface, experimentally measured by the shadowgraphs taken before and after the fillet rolling, was used as the boundary condition under a deformation-controlled procedure. Spiteri et al. [19] assumed that the induced residual stress was greatly affected by the rolling force in the ramping up and down stages. In another word, additional operation in the full load stage was considered not to significantly increase the magnitude, or alter the distribution of the residual stress. In their model, a 2D plane strain target was loaded up to a maximum by the roll and then unloaded to drive the residual stress. The same assumption was also made elsewhere [20,21]. Majzoobi et al. [12] presented a 3D finite element simulation of a flat target rolled by a rigid body. However, the residual stress field predicted by the model was not compared with the experimental measurements to evaluate the accuracy of the simulation. The present shortcomings in the simulation of deep rolling will be addressed in this work by developing a more realistic finite element model.

Notwithstanding the significant role of residual stress for a successful deep rolling, the present work aims to provide a comprehensive insight using both experiments and simulations. The target component is a full-scale railway axle for high speed applications. Railway axles are one of the most critical mechanical components as regards safety. The railway axles are usually designed for an infinite life using admissible stress levels, which corresponds to generous safety factors applied to full-scale fatigue properties of materials [22,23]. Nevertheless, some failures still occur due to fatigue cracks generated during service, by corrosion-fatigue phenomena or ballast impacts [24–26]. In order to avoid such failures, which are related to a number of factors not easily predictable (see for example [27]), a suitable inspection strategy is supported by "damage tolerant" analyses [28–30]. A quite novel possibility is to consider the application of compressive residual stresses at the surface of the axles. Compressive residual stresses decrease crack propagation driving forces. This solution is mainly applied to freight applications nowadays, and also to high-speed ones in some European countries. A successful example, related to railway axles, is the application of induction hardening to increase the fatigue strength of the press-fit seats, where typically suffer from fretting-fatigue [31,32]. Other surface treatments like oxynitrocarburizing and shot peening were affirmed to have beneficial effects on fatigue limit of railway axle steels [33,34]. However, those have not been tested on a full-scale axle.

The present study explores the feasibility of performing deep rolling on full-scale railway axles. Generated surface residual stresses were measured by X-ray diffraction (XRD) and hole-drilling (HD) methods along the axle axis. In depth measurement of residual stress distribution was also carried out at different selected locations. The depth of the hardened layers was also characterized by XRD. A realistic finite element simulation of deep rolling is developed and validated. Accordingly, a parametric study is performed to study the effect of rolling force, rolling feed, roll geometry and also deep rolling coverage on the distribution of residual stresses and the induced hardening. Finally, the obtained parametric residual stress profiles are introduced in a simple crack propagation algorithm to analyze the influence of the technological parameters on lifetime of railway axles, by both "one-parameter-at-a-time" and "Design of Experiments" methodologies.

2. Material and experiments

2.1. Material

The material considered in this study is the EA4T (quenched and tempered 25CrMo4) steel grade, one of the standardized European steels used for the production of railway axles [35]. Its nominal chemical composition [24] is summarized in Table 1. The mechanical properties were evaluated through monotonic, low-cycle fatigue (LCF) and crack propagation tests.

2.2. Monotonic and cyclic behavior

Monotonic tensile tests were carried out following the suggestions given by the ASTM E8 standard [36]. Two dog-bone cylindrical specimens were tested by an electro-mechanical mono-axial machine with a 100 kN load cell and an extensometer. The experimental monotonic stress–strain curves of the material are shown in Fig. 1a, while Table 2 summarizes the obtained mechanical properties as the mean value of the two tests.

Seven dog-bone specimens were subjected to strain-controlled fatigue tests to obtain the low cycle fatigue (LCF) behavior of the material. The tests were carried out using a servo-hydraulic mono-axial machine with a 100 kN load cell and an extensometer at $R = -1$ and at a frequency of 1 Hz. The tests were carried out following the suggestions given by the ASTM E606 standard [37] adopting the "single step" methodology. The strain ranges applied to the seven specimens were ±0.23%, ±0.27%, ±0.3%, ±0.4%, ±0.5%, ±0.6% and ±0.7%. The cyclic curve was derived (Fig. 1b) by interpolating the tips of the stabilized, i.e. acquired at half the fatigue life of each specimen, hysteresis loops. Accordingly, the Ramberg–Osgood relationship (Eq. (1)) was adopted for the present material.

$$\varepsilon = \frac{\sigma}{E_c} + \left(\frac{\sigma}{H}\right)^{1/n} \quad (1)$$

The obtained empirical parameters E_c, H and n are shown in Table 2 together with the cyclic yield stress $R_{p0.2c}$. The derived cyclic curve is compared to the monotonic ones in Fig. 1a, where a significant softening behavior of the material can be observed during cyclic loading.

2.3. Crack propagation behavior

Due to the superposition of compressive residual stresses and in-service rotating bending, the stress ratio acting at the surface of the axle will be different, in particular much lower than the typical $R = -1$ value adopted in rotating bending test. From this point of view, a dedicated experimental campaign was carried out, in order to investigate the crack propagation behavior of the EA4T grade in the not-yet-explored region of very negative stress ratios. Full details of this activity are reported in [38], while a short summary of the tests is as follow. Specimens with single edge in bending, SE(B), and single edge in tension, SE(T), were prepared and tested using the compression pre-cracking approach [39,40]. SE(B) specimens were tested at different stress ratios ranging from $R = 0.7$ to $R = -2.5$. In order to obtain relevant results for even more negative stress ratios, SE(T) specimens were tested at different stress ratios ranging from $R = -2.5$ to $R = -4$. All data were then interpolated by Nasgro equations [41] for the FCG lifetime predictions described in Section 4.4.

2.4. Deep rolling of full-scale railway axle

The scheme of the full-scale railway axle studied in this work, and typically adopted for high-speed applications, is shown in Fig. 2a. The axle was deep-rolled along the body (including

Table 1
Nominal chemical composition of EA4T steel grade (weight %).

C	Mn	Si	Cr	Mo	Ni	V	S	Cu	Pa
0.22–0.29	0.5–0.8	0.15–0.4	0.9–1.2	0.15–0.3	0.3	0.06	0.015	0.3	0.02