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Optimization of the cold-rolling process to enhance service life of railway axles

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Abstract

Over the last years, deep rolling has been adopted to improve the fatigue strength of railway axles. In particular, recent researches between PoliMi and LucchiniRS have shown the possibility to greatly enhance the residual lifetime of axles in presence of defects from running in service by inhibiting the propagation of cracks under normal loading conditions and retarding the appearance of corrosion-fatigue phenomena. Therefore, the new automatic machining line for axles setup by LucchiniRS includes a modern cold-rolling machine as a finishing process for premium quality axles. This paper is devoted to discuss the optimization of the cold-rolling process considering all the relevant parameters (load, roller radius, pitch) through a novel model able to simulate the build-up of residual stresses. The model was validated by comparing the residual stress path with the experimental outcomes, showing a good agreement for the various combination of the adopted parameters. The exploitation of the model will enable the designer to optimize the cold-rolling process taking advantage of the increase of fatigue properties in the definition of a safe life maintenance plan.

Keywords: cold-rolling, residual stresses, crack propagation

1. Introduction

Railway axles are safety critical components, designed for infinite life, typically set in 30 years of service, whose failure may result in derailments, with serious damage for the rolling stock, the infrastructure, or even worst, to injuries to people. Despite these components are designed for an infinite life, EN 13103 (2001) and EN 13104 (2001), the design approach has been in the last years more and more complemented by the damage tolerant one, where the presence of defects arising from service is accepted, Grandt (2004); Zerbst et al. (2013); Cantini et al. (2011). Even if these defects can happen and grow, the safety of the axle is ensured, by this methodology, by the regular

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in-service inspections during the life of the train. For this reason, the resistance against failure in service is a key issue in designing the axle and in its related maintenance plan in service, to ensure high safety standards and, at the same time, to optimize life-cycle costs. More than a meticulous definition of the service inspection plan, any methodology able to increase the lifetime of a real axle subjected to service, with the possibility of damaging in line, is particularly appreciated. Among them, the presence of compressive residual stresses on the axle is one of the strategies for increasing lifetime by reducing the stress intensity factors (SIFs) experienced by an eventual crack. This paper will focus to the definition of an analytical tool for the calculation of the residual stresses in railway axle after the cold rolling procedure.

2. The adoption of cold rolling to enhanced service life of railway axle

The presence of a compressive residual stress field is always desirable for all the components which are designed for a very long life and are safety components, like railway axles are. While the quenching and tempering process can result in slightly compressive stresses under the surface, the reachable values and depths are not sufficient to effectively prevent the propagation of defects which can typically happen from the running in service, like impact from ballast, scratches or corrosion pitting.

Considering the railway axle sector, the technological process traditionally adopted by axle producers for the life extension is cold rolling. By this procedure, see Altenberger (2005), a roller translates along the whole surface of the axle, or just along those regions which are recognized as critical, inducing local plastic deformations which results at the end in compressive residual stresses.

The compressive residual stresses at the end of the cold rolling technological process typically stay in the first 3 mm in depth, having values in the range of -600 MPa along the longitudinal direction (the axis direction) and about -300 MPa along the circumferential one, as measured from previous work from the authors. Such a magnitude of residual stresses suggests an effective prospective action against crack propagation in full scale axles, where, usually, the maximum in-service stress amplitude is lower than 200 MPa.

Previously carried out tests, by Regazzi et al. (2014), have shown that, after cold rolling, notches up to 4 mm, which are supposed to be easily detectable during in-service inspections, propagates with very slow speed rate and only with load spectra higher than normal, increasing the lifetime of the axle or, alternatively, increasing the safety of the axle during its life.

The relevant technological parameters, depending on the desired magnitude of residual stresses and their maximum depth, are the geometry of the roller at the contact region, meaning basically its radius, the longitudinal feed (the step of advancement per turn along the axis) and the applied contact force, as shown for example in Altenberger (2005). The definition of such parameters is very important in the fine-tuning of the process, since the experimental evaluation of the residual stresses under the surface is a very long and costly process, requiring a huge amount of measurements by XRD methodology, which is typically beyond the scopes and the time availability of the production line.

For such reason, the development of an analytical model able to properly and quickly define the parameters of the process given the required amount of residual stresses and their depth, is very important in the optimization of the production process.

3. Modelling of residual stresses

The analytical model for the prediction of the residual stresses induced by cold rolling is based on the original model proposed by Guechichi et al. (1986) for predicting the residual stresses due to shot-peening.

The model assumes a periodic time dependent stress field as a linear combination of the elastic stress field and the residual stress field:

$$\boldsymbol{\sigma} = \boldsymbol{\sigma}^{el} + \boldsymbol{\sigma}^{r} \tag{1}$$

where bold denotes a tensor quantity. The elastic stress field $\boldsymbol{\sigma}^{el}$ due to the applied Hertzian pressure has been computed with the equation proposed by Sackfield and Hills (1983). The contact area dimensions are related to the roller radii, the applied contact force and the shape of the cold rolled part. The approximate analytical model of Hertzian theory proposed by Antoine et al. (2006) has been applied to calculate the dimension a, b of the elliptical area of contact and the Hertzian contact pressure. The residual stress field is approximated by considering the vertical residual stress small if compared to the longitudinal and circumferential residual stress leading to the condition: $\sigma_z^r = 0$.

The total strain during the roller passage can be written in terms of an inelastic portion and an elastic one:

$$\boldsymbol{\epsilon} = \boldsymbol{\epsilon}^{el} + \boldsymbol{\epsilon}^{ine} = \boldsymbol{\epsilon}^{el} + \boldsymbol{\epsilon}^{p} + M\boldsymbol{\sigma}^{r} \tag{2}$$

where the inelastic portion is a superposition of the irreversible plastic strain and the strain resulting from the residual stresses. The strains corresponding to the residual stresses are governed by the law of elasticity by considering the elastic compliance matrix M. The inelastic strains after each passage of the load are assumed to be zero except for the vertical component, i.e. $\epsilon_z^{ine} \neq 0$.

In the framework of a cyclic plasticity model, the irreversible plastic strain increment can be obtained with the normality flow rule:

$$\mathrm{d}\boldsymbol{\epsilon}^{p} = \mathrm{d}p \cdot \boldsymbol{n} \tag{3}$$

where $\boldsymbol{n}$ is the unit exterior normal to the yield surface for a given deviatoric stress state and $\mathrm{d}p$ is the equivalent plastic strain increment:

$$\mathrm{d}p = \sqrt{\mathrm{d}\boldsymbol{\epsilon}^{p} : \mathrm{d}\boldsymbol{\epsilon}^{p}} \tag{4}$$

The condition on the inelastic strains at the end of the cold rolling process together with Eq. 2 and Eq. 3 allow to define the residual stress increment with respect to the equivalent plastic strain increment:

$$\frac{\mathrm{d}\boldsymbol{\sigma}^{r}}{\mathrm{d}p} = \begin{bmatrix} -\frac{E}{1-\nu^2}\left(n_x + \nu n_y\right) & -2Gn_{yx} & -2Gn_{zx} \\ -2Gn_{xy} & -\frac{E}{1-\nu^2}\left(n_y + \nu n_x\right) & -2Gn_{zy} \\ -2Gn_{xz} & -2Gn_{yz} & 0 \end{bmatrix} \tag{5}$$

and the corresponding deviatoric residual stress increment $\boldsymbol{\rho}$:

$$\frac{\mathrm{d}\boldsymbol{\rho}}{\mathrm{d}p} = \frac{\mathrm{d}\boldsymbol{\sigma}^{r}}{\mathrm{d}p} - \boldsymbol{I}\frac{(\mathrm{d}\boldsymbol{\sigma}^{r}/\mathrm{d}p)_{ii}}{3} = K_{\rho}\boldsymbol{n} \tag{6}$$

This result can be used in a cyclic plasticity model by defining the yield surface:

$$\sqrt{(\boldsymbol{S} - \boldsymbol{\alpha}) : (\boldsymbol{S} - \boldsymbol{\alpha})} - \sqrt{2}k = 0 \tag{7}$$

with $\boldsymbol{S}$ representing the deviatoric stress tensor, $\boldsymbol{\alpha}$ the backstress tensor and k the cyclic yield shear stress. The non-linear kinematic hardening rule is expressed following the Chaboche decomposition of the backstress, Chaboche et al

(1979):

$$\mathrm{d}\boldsymbol{\alpha}_k = \tfrac{2}{3}C_k\boldsymbol{n}\mathrm{d}p - \sqrt{\tfrac{2}{3}}\gamma_k\boldsymbol{\alpha}_k\mathrm{d}p \qquad \boldsymbol{\alpha} = \textstyle\sum_{k=1}^{N}\boldsymbol{\alpha}_k \tag{8}$$

The non-proportional hardening induced by the rolling contact stress is taken into account by defining a variation of the shear yield stress k as proposed by Tanaka (1994):

$$\tfrac{\mathrm{d}k}{\mathrm{d}p} = b_0\,(k_T - k) \qquad k_T = k_0 \exp\left(N_p A\right) \tag{9}$$

with the introduction of two additional material parameters, N_p and b_0, and the Tanaka's parameter A used to quantify the amount of non-proportional hardening starting from the definition of a fourth order tensor which is a function of the plastic strain and the direction of the plastic strain increment.

Considering Eq. 7 and writing Eq. 1 in terms of deviatoric stress, it is possible to rewrite the yield surface as:

$$\left(\boldsymbol{S}^{el} - \boldsymbol{\alpha}^*\right) : \left(\boldsymbol{S}^{el} - \boldsymbol{\alpha}^*\right) - 2k^2 = 0 \tag{10}$$

where $\boldsymbol{\alpha}^*$ is a new second tensorial internal variable:

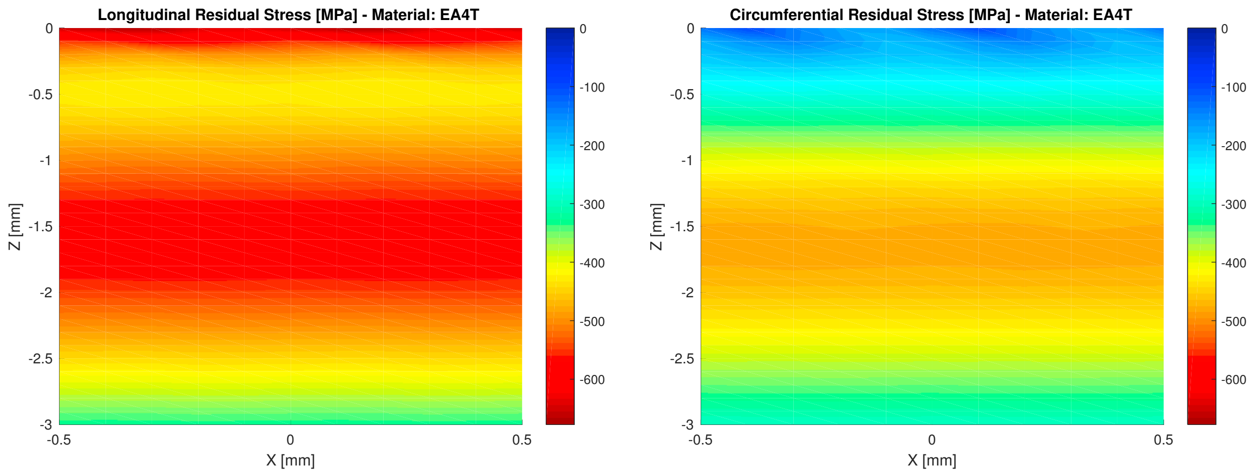
$$\boldsymbol{\alpha}^* = (\boldsymbol{\alpha} - \boldsymbol{\rho}) \tag{11}$$

The modified backstress, $\boldsymbol{\alpha}^*$, is used to relocate the yield surface to a location in stress space depending on the residual stress:

$$\frac{\mathrm{d}\boldsymbol{\alpha}^*}{\mathrm{d}p} = \sum_{k=1}^{M}\left(\frac{2}{3}C_k\boldsymbol{n} - \sqrt{\frac{2}{3}}\gamma_k\boldsymbol{\alpha}_k\right) - K_\rho\boldsymbol{n} \tag{12}$$

By imposing the consistency condition during the load passage:

$$\left(\boldsymbol{S}^{el} + \mathrm{d}\boldsymbol{S}^{el} - (\boldsymbol{\alpha}^* + \mathrm{d}\boldsymbol{\alpha}^*)\right) : \left(\boldsymbol{S}^{el} + \mathrm{d}\boldsymbol{S}^{el} - (\boldsymbol{\alpha}^* + \mathrm{d}\boldsymbol{\alpha}^*)\right) - 2\,(k + \mathrm{d}k)^2 = 0 \tag{13}$$



(a) (b)

Fig. 1. Residual stress prediction: a) Longitudinal residual stress; b) Circumferential residual stress. X: longitudinal direction; Z: depth.

the equivalent plastic strain increment can be obtained and the values of k, $\boldsymbol{\alpha}$ and $\boldsymbol{\rho}$ can be updated:

$$\begin{aligned} \mathrm{d}p \rightarrow \quad & \mathrm{d}\boldsymbol{\epsilon}^p = \boldsymbol{n}\mathrm{d}p \rightarrow \boldsymbol{\epsilon}^p = \boldsymbol{\epsilon}^p + \mathrm{d}\boldsymbol{\epsilon}^p \\ & \mathrm{d}k = \left(\frac{\mathrm{d}k}{\mathrm{d}p}\right)\mathrm{d}p \rightarrow k = k + \mathrm{d}k \\ & \mathrm{d}\boldsymbol{\alpha} = \left(\frac{\mathrm{d}\boldsymbol{\alpha}}{\mathrm{d}p}\right)\mathrm{d}p \rightarrow \boldsymbol{\alpha} = \boldsymbol{\alpha} + \mathrm{d}\boldsymbol{\alpha} \\ & \mathrm{d}\boldsymbol{\rho} = \left(\frac{\mathrm{d}\boldsymbol{\rho}}{\mathrm{d}p}\right)\mathrm{d}p \rightarrow \boldsymbol{\rho} = \boldsymbol{\rho} + \mathrm{d}\boldsymbol{\rho} \end{aligned} \tag{14}$$

3.1. Residual stress prediction

An example of application of the analytical model is showed in Fig. 1 for a specific set of rolling parameters. In Fig. 2 the results in the midsection are shown. The analytical model can be used to quickly investigate the effect of rolling force, rolling feed and roll geometry on the distribution of residual stresses

3.2. Comparison with experimental results

An experimental study, based on an in depth measurement of residual stress on deep rolled full-scale specimens, has been used to validate the analytical model. For this purpose, two axles made of EA4T steel grade were machined, based on a trailer axle design with two brake disc seats, as can be seen in Fig. 3. Each axle was subjected to cold rolling using one roller radius per axle and applying four different load levels for each diameter of the axle. Given the two axles, the two rollers and the load levels, a total of 32 combinations were prepared. In order to obtain results useful for the serial production, the chosen parameters are close to the ones usually adopted: the two chosen rollers have radiuses 12 mm and 25 mm, being the most widely adopted for the cylindrical portions and for the transitions. The diameters of the various portions of the axle vary from 130 mm of the journals to the 210 mm of the wheel seats, including a 200 mm for the brake disc seats and a 175 mm for the axle body. The values of the forces used for each roller during the test are collected in Table 1.

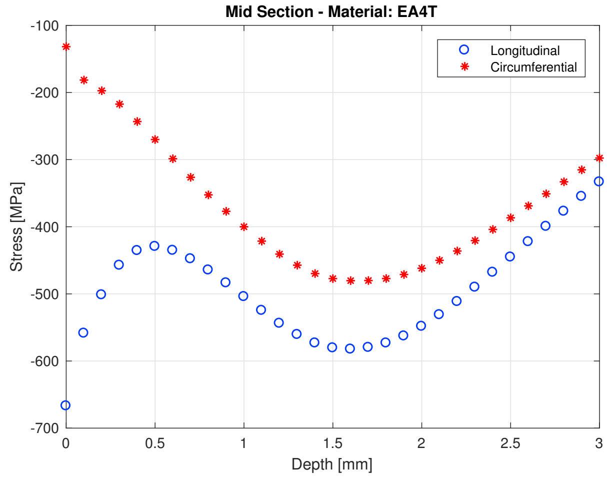


Fig. 2. Residual stress prediction in the midsection (X = 0).

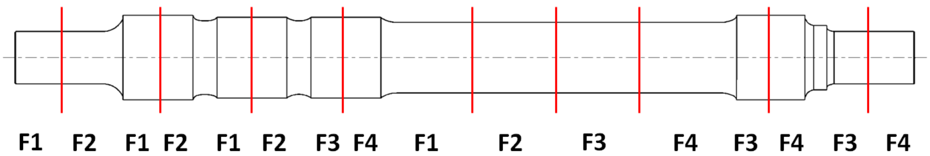


Fig. 3. Geometry of the axles and scheme of the forces applied for the cold-rolling.

After the machining of the cold-rolled axles, with the described parameters, the hardness increment on the various portions was measured, showing an increment in the local hardness of about 18-25%, which can be directly linked to an increment in the fatigue properties of the material. An investigation on the resulting residual stress profile was carried on for each of the 32 combinations roller-diameter-force, by meaning of the XRD methodology. The outer surface of the axle, as well as two points at 1 mm and 2 mm in depth, after an electrolytic attack (ECM) in order not to affect the residual stress path, were investigated and the results compared with the outcomes of the calculation.

Roller	F1 [kN]	F2 [kN]	F3 [kN]	F4 [kN]
R12	8	10	12	14
R25	14	18	22	26

Table 1. Forces used for the cold-rolling of the two axles.

The comparison between the experimental and analytical results is shown in Fig. 4 at 1 mm depth and 2 mm depth. The results of the calculation are in good agreement with the experimental outcomes, for both the longitudinal and the circumferential directions. By these results, adopting the typically parameters of the serial production, it can be seen that the residual stresses at 1 mm and especially 2 mm are very high in compression, around 500 MPa in the longitudinal direction and a little less in the circumferential one. As already proved by Regazzi et al. (2014) these compressive residual stresses are adequate to fully stop the propagation of a 2 and 3 mm initial crack on a real application axle under normal service, being these crack sizes the typically dimensions 100% detectable by non-destructive UT inspections, and to retardate significantly the propagation of 4 mm cracks, usually considered as very big cracks.

After having proved the capacity of the implemented analytical instrument to properly predict the effect of the various parameters in the cold rolling process, it can now be adopted to fine tune the process, based on the desired residual stress values and depth. For example, an interesting parameter which effect is not easy to experimentally determine is the longitudinal feed to assign to the process in order to have an homogeneous pattern of the resulting

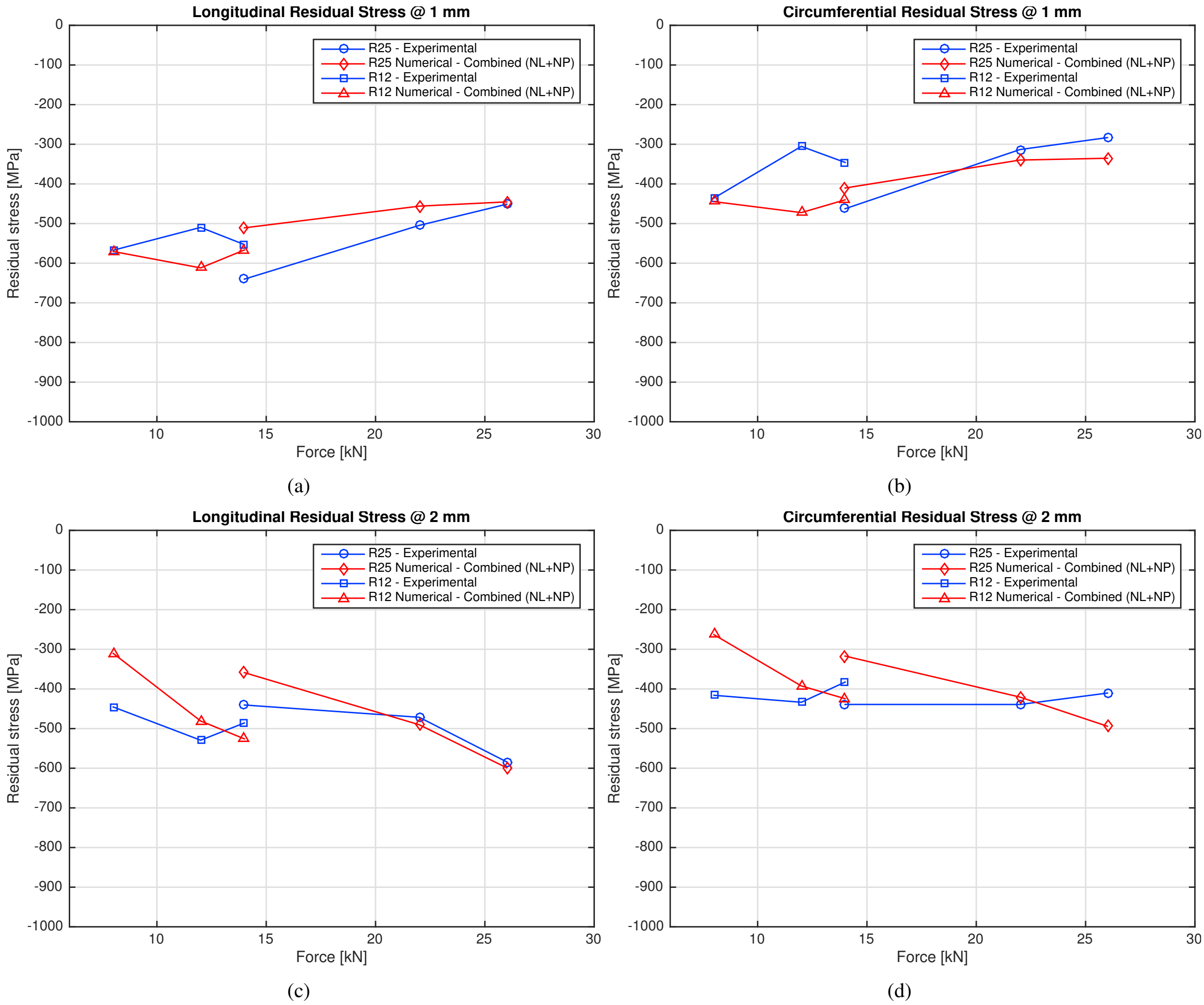


Fig. 4. Comparison with experimental results. a) Longitudinal residual stress at 1 mm depth; b) Circumferential residual stress at 1 mm depth; c) Longitudinal residual stress at 2 mm depth; d) Circumferential residual stress at 2 mm depth. R25: roller radius 25 mm; R12: roller radius 12 mm; Combined (NL+NP): analytical model with non-linear/non-proportional combined kinematic hardening.

stresses: decreasing the feed will result in a more homogeneous stress pattern, but in a very long machining time. The developed tool can provide some useful informations for the optimization of both the process and the results. An example of the effect of the longitudinal feed is shown in Fig.5. The image on the left corresponds to a rough advancement, not able to return the regular path required, while the image on the right correspond to a more refined feed, resulting in a more regular path.

4. Conclusion

As proved in last years, cold rolling is an effective process for the lifetime extension of railway axle even in presence of defects typically arising from service, which can be fully stopped or highly retarded in their propagation, allowing to a longer distance between the inspections or to an increase in the safety factor of the maintenance plan. Moreover, last activities carried out by the authors have proved an increase of the fatigue limit of the axles higher than 25% and the ability of the cold rolling to inhibit the development of the corrosion fatigue phenomenon. For this

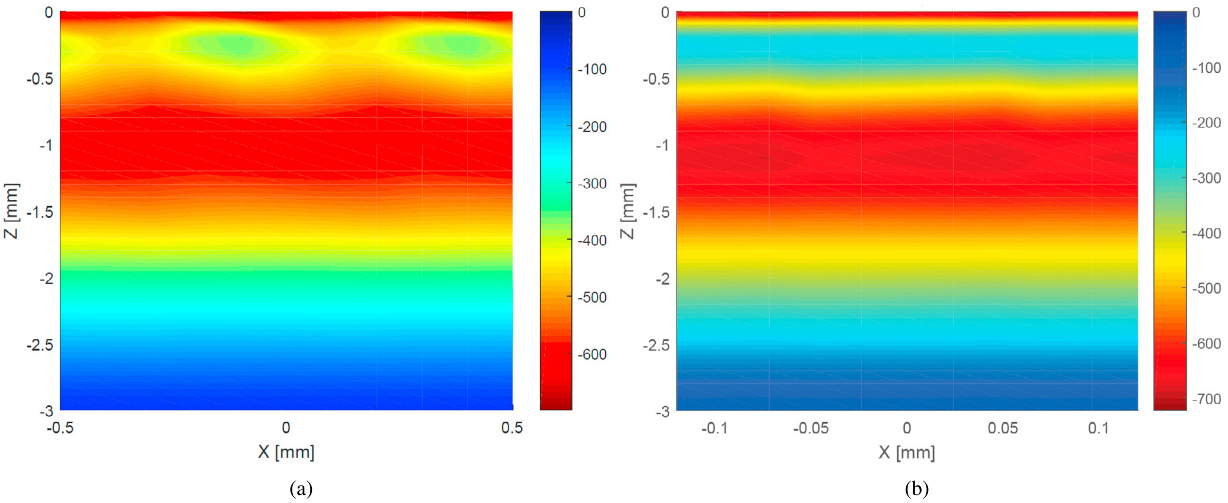


Fig. 5. Effect of the longitudinal feed in the residual stress distribution: a) Longitudinal residual stress; b) Circumferential residual stress. *X*: longitudinal direction; *Z*: depth.

reason the process has been more and more offered by LucchiniRS for their premium quality axles. The developed analytical algorithm allows to a better definition of all the technological parameters involved in the process, giving an useful instrument to both the designer and the production line.

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