International Journal of Mechanical Sciences 123 (2017) 106–116

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

# Effects of local overloads on cold rolling mill work rolls

V. Vinogradov[a,*], M. Knyazhansky[b], A. Tsun[c]

[a] School of Civil Engineering and Geosiences, Newcastle University, Newcastle upon Tyne NE1 7RU, UK
[b] Department of Software Engineering, Shamoon College of Engineering, Beer-Sheva 84100, Israel
[c] Raymond and Beverly Sackler Faculty of Exact Sciences, School of Physics and Astronomy, Tel-Aviv University, Tel-Aviv 69978, Israel

ARTICLE INFO

*Keywords:*
Case hardening
Plastically graded materials
Plastic zone
Hertzian contact
Contact overloading

ABSTRACT

Local overloading is one of the most common reasons for premature failures of cold rolling mill work rolls. Case-hardened rolls demonstrate spatial variation of the material hardness and yield strength with a decreasing profile with depth and belong to the class of so-called plastically graded materials. Contact overloads cause formation of subsurface closed-shape plastic zones, accompanied by a significant perturbation in the stress field. In the present paper the effect of an overload on a case-hardened roll is numerically modelled using finite element, when the parameters of the contact loads are chosen to represent a common situation when an accidentally formed strip fold enters the roll bite. It is shown that plastic deformations in the graded layer originate at depths, which significantly exceed the depth of the maximum effective stresses, determined by the elastic solution. During the contact overload, tensile stresses develop at the upper boundary between the elastic and plastic zones. Tensile stresses at the free surface in the vicinity of the contact zone increase up to ten times due to formation of the subsurface plastic zone. Residual stresses with a very large tensile hydrostatic component are shown to appear in the unloaded material. These tensile stresses, both operational and residual, can cause premature spalling in the contact surface during either the overloading or further operation of the roll. It is shown that an increase in the depth of the hardened case and increase in the roll core hardness allows to reduce plastic deformations during overloads, reduce both operational and residual stresses in the graded layer and shift formation of the plastic zone deeper from the surface and the contact zone, which decreases the chances of premature spalling.

## 1. Introduction

Work rolls of cold rolling mills experience high contact loadings during their life. A roll system and a draft schedule of the rolled strip are usually designed such that the stresses acting at the roll-strip contact zone and near-contact zones within the work rolls do not exceed 50–90% of the elastic limit (or the yield stress $\sigma_Y$) of the roll material [1,2]. When the contact length of two contacting bodies significantly smaller than their size, the distribution of the effective stress as well as the maximum shear stress along the depth direction exhibits a maximum. In the simplest case of frictionless contact of two cylinders, the peak of the distribution is located on the axes of symmetry at depth 0.4–1.0 of half the contact length, depending on the contact pressure distribution, and at 0.785 of half the contact length in the classical Hertz contact problem when the contact pressure has an elliptical distribution along the contact. The maximum value of the distribution is mainly determined by the maximum value of the contact stresses, while the depth depends on the contact length. If frictional forces are present at the contact zone the distribution maximum is shifted closer to the surface [3]. In order to increase the contact strength of the rolls they undergo surface hardening (quenching), followed by tempering. Surface or case hardening to the designed depth mentioned above increases the hardness and the yield stress of the surface layers and leads to the situation when the maximum effective stress is below the *local* elastic limit of the roll material. This ensures long-term life of the strengthened rolls without the inception of plastic deformations and irreversible damage in the designed working regimes. The profile of the yield strength with depth is hence non-uniform decreasing nonlinearly from the high strength at the near-contact surface to a lower in the core; the elastic properties of the material are practically remain unchanged. The roll material can then be considered as elastically homogeneous with a plastically graded surface layer.

The situation changes significantly when in some areas of the contact region the operating stress exceeds the local elastic limit and the material transfers into the elastic-plastic state. This not rarely happens in practice due to accidental overloads [4–6]. A very common

* Corresponding author.
*E-mail address:* Vladimir.Vinogradov@newcastle.ac.uk (V. Vinogradov).

http://dx.doi.org/10.1016/j.ijmecsci.2017.01.046
Received 14 July 2016; Received in revised form 13 January 2017; Accepted 30 January 2017
Available online 04 February 2017

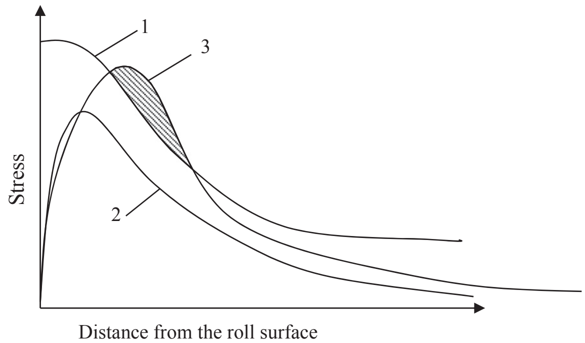


**Fig. 1.** Inception of the plastic zone in the graded layer of the roll: 1 – distribution of the yield stress of the material; 2 – distribution of effective stresses under normal rolling conditions; 3 – distribution of the effective stress during passage of folds.

issue in the steel industry is when the rolled strip folds ("pinches") in the roll bite due to strip breakage or non-uniform deformation of the strip across its width (see e.g. [5,6]), which can occur for several technological reasons [7–9].

Fig. 1 schematically shows the distribution of the yield strength along the depth of hardened zone $\sigma_s$ (curve 1) and the values of the effective stress $\sigma_i$ on the symmetry axis of the loading area (curve 2), corresponding to regular working conditions. During the passage of the strip folds through the roll gap, the contact stresses and hence the effective stress $\sigma_i$ increase significantly (curve 3) and becomes greater than the yield strength (shaded area), which leads to a transition of the region into the plastic state. At this moment the original linear problem of loading of the elastic homogeneous body turns into a nonlinear problem of deformation of a plastically graded body, i.e. deformations of an elastic body with a pliant elastic-plastic inclusion with evolving boundaries influenced by the boundary conditions at the contact.

Practical research has established an unequivocal relationship between local overloads and subsequent damage (spalling, delamination, cracks) in the case-hardened rolls [7,9]. In the present paper numerical modelling of contact overloads is presented with particular attention to development of plastic deformation and both operating and residual stress perturbations in the case-hardened materials in an attempt to estimate the effects of overloads on further material durability.

## 2. Evaluation of force and geometrical parameters of local overloads

In this section an estimate is presented for the contact loads in the roll bite in normal operational conditions and in the incidental situation, when a triple fold passes through the roll bite. The exercise is for illustrative purposes only. The goal is to estimate the possible range of the normal contact loads and to demonstrate the potential of joint plastic deformation of the strip and the roll in the abnormal loading conditions.

Parameters of deformation during the passage of a triple strip thickness are estimated using the model suggested by Tselikov, see e.g. [7,8]. The actual length of the deformation zone is determined by the method of Hitchcock, described in e.g. [1,10–12], which takes into account the roll flattening effect. The results of calculations for a low-carbon steel are shown in Table 1. The diameter of the work rolls is taken $D = 500$ mm and for normal operation the relative reduction is 25%.

Our calculations indicate that the contact pressure in of triple thickness through the roll bite increases by 3–5 times, while the total loads increase even more intensively by up to 8 times, and the contact length increases by 3–4 times.

Due to the assumed incidental overloading the relative draft increases from 25% to about 70%. The coefficient of friction increases from ~0.1 to ~0.2 (and more) due to discontinuities in the lubricant layer between the roll and the strip (partially dry friction). The values for the coefficient of friction during cold rolling with and without lubrication are chosen from the data presented in Table 3.12 in [10]. Specific contact pressure increases significantly when the thickness of the strip approaches the limiting (minimum possible) thickness $h_{min}$, which is roughly determined by the relation [13,14].

$$h_{min} = 3.62 fDK_1/E, \tag{1}$$

where $E$ is the Young modulus of the material and $K_1$ is the constrained yield stress, for details see e.g. [1,12]. Therefore, the roll gap, set for normal operation regimes (for instance, 1 mm), can become less than $h_{min}$ due to the increased coefficient of friction (for $f = 0.2$ the limiting minimum thickness is already 1.034 mm, which is higher than the considered roll gap). The relation (1) is also shown graphically in Fig. 2 for illustration. In these situation, a joint plastic deformation of both the strip and the rolls becomes possible.

## 3. Problem formulation

Previous experiments and numerical modelling of local contact loading of cylinders with a plastically graded surface layer [15] have shown that plastic deformation initiates with formation of a closed-shape plastic region at some depth without reaching the surface. Maximum plastic strains form at the depths of $1.5 - 2$ of half the contact length $b$, which exceed the depth at which the maximum effective stress develops in purely elastic contact conditions ($0.785b$, according to the Hertz solution). Due to the spatial variation of the yield strength the plastic zones are shifted deeper towards the layers of lower values of the yield stress, while an extended narrow zone below the contact area remains elastic, behaving as an elastic beam on a ductile substrate.

In order to understand the inception and development of plastic deformation in a case-hardened roll due to passage of a fold through the roll bite, a simpler problem is formulated herein. We consider a two-dimensional problem of a case-hardened half-plane, representing the roll, with a plastically graded surface layer in contact with an elastic circular disc, while the total contact load and the radius of the disc are chosen such that the corresponding loading parameters (mean load pressure $p$ and contact length $2b$) are in accordance with the estimates of the illustrative example, described in the previous section (Table 1). Validation of the model can be found in [15]. The straight boundary eliminates the influence of the contact surface curvature of the plastically graded body on the distribution of stress/strain fields in the near-contact zones. However, for contact lengths comparable with the depth of the hardened layer and radii of the work roll significantly greater than the contact zone length, this is seen as an acceptable approximation. Contact is treated as frictionless. The influence of contact friction, the shape of the distribution of contact stresses along the contact and the curvature of the contact surface will be discussed elsewhere.

The required radius $R$ of the pressing disc was determined using the Hertz solution:

$$b = \sqrt{\frac{8F_nR}{\pi E_e}}, \tag{2}$$

where $F_n$ is the force pushing the disc onto the half-plane (per unit thickness), and $E_e$ is the combined Young's modulus, determined by the expression

$$E_e = \frac{2E_cE_p}{(E_c + E_p)(1-\nu^2)}. \tag{3}$$

The origin of coordinate system is placed in the middle of the contact area, the $X$-axis points horizontally to the right along the contact surface and the $Y$-axis upwards, being the axis of symmetry.