Editorial Manager(tm) for Ironmaking and Steelmaking: Processes, Products and Applications
Manuscript Draft

Manuscript Number:

Title: SLEEVED ROLLS - An Old Idea, New Possibilities

Article Type: Special Issue Article

Keywords: Rolling mill; Sleeved rolls; Backup rolls; Hot rolling; Shrink fitting

Corresponding Author: Dr Daniel Hajduk, Ph.D.

Corresponding Author's Institution: ITA Ltd.

First Author: Daniel Hajduk, Ph.D.

Order of Authors: Daniel Hajduk, Ph.D.; Radim Pachlopník; Zdeněk Bembenek; Bronislav Molinek

Abstract: The idea of sleeving is rather old. A presence of permanent tensile stress in sleeves, that may lead to cracks, handicapped these types of rolls. But the development in mathematical modeling, metallurgy, non-destructive metal testing and other branches enabled to produce sleeved rolls with similar or better properties than the solid ones.
The paper deals with techniques, that allow to reduce the level of permanent tensile stresses such as computer simulation. Complex design of sleeved rolls including the shape optimalization of sleeve and arbor, design of chamfers on backup rolls reducing hertzian contact stresses and design of roll grinding will be described. A comparison of measured and computed residual stresses in the sleeve after a thermal treatment will be presented. At the end practical experience with sleeved rolls in hot rolling mills will be discussed.

SLEEVED ROLLS

– AN OLD IDEA, NEW POSSIBILITIES

Authors:

- Daniel Hajduk
  ITA Ltd., Martinská 501/6, 709 00 Ostrava, Czech Republic, mail@ita-tech.cz

- Radim Pachlopník
  ArcelorMittal Ostrava Inc., Vratimovská 689, 707 02 Ostrava-Kunčice, Czech Republic, radim.pachlopnik@mittalsteel.com

- Zdeněk Bembenek
  DEVIMEX Ltd., 17.listopadu 1790/5, 708 52 Ostrava-Poruba, Czech Republic, devimex@devimex.cz

- Bronislav Molinek
  DEVIMEX Ltd., 17.listopadu 1790/5, 708 52 Ostrava-Poruba, Czech Republic, devimex@devimex.cz

ABSTRACT

The idea of sleeving is rather old. A presence of permanent tensile stress in sleeves, that may lead to cracks, handicapped these types of rolls. But the development in mathematical modeling, metallurgy, non-destructive metal testing and other branches enabled to produce sleeved rolls with similar or better properties than the solid ones.

The paper deals with techniques, that allow to reduce the level of permanent tensile stresses such as computer simulation. Complex design of sleeved rolls including the shape optimalization of sleeve and arbor, design of chamfers on backup rolls reducing hertzian contact stresses and design of roll grinding will be described. A comparison of measured and computed residual stresses in the sleeve after a thermal treatment will be presented. At the end practical experience with sleeved rolls in hot rolling mills will be discussed.

KEYWORDS

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1. INTRODUCTION AND MOTIVATION

Sleeving rolls is most frequently used as a method of:

- Repair of older rolls
- Manufacturing of huge rolls that cannot be made as solid ones
- Cheaper alternative to solid rolls (with multiple use of an arbor)

Economical aspects of sleeved rolls together with rapid increase of roll prices in the world market have lead to enormous demand on sleeved rolls recently, especially when strip producers had several damaged older solid rolls.

A sleeved roll consists of an arbor and a sleeve that are joint by shrink fit. This produces a permanent tensile stress in the sleeve which potentially may lead to fracture. To avoid this, dangerous tensile stresses must be minimized. It is possible by more precise computer simulations using multidimensional numerical methods (FEM), better material of sleeves with suitable thermal treatment and controlled cooling/heating of sleeve in process of shrinking. An important role in achieving of long service life is the use of non-destructive testing to detect micro-cracks after each roll campaign.

2. SHRINK FIT DESIGN

As mentioned above, shrink fit between sleeve and arbor must be designed very carefully with minimum overlap that produces low tensile stresses. The only condition for dimensioning is a satisfactory transfer of loads between an arbor and a sleeve in all temperature regimes of the roll. In backup rolls (BuR) it is mainly bending moment; in work rolls (WR) working in 4h stands it is rolling torque that must be transferred without slipping.

The design of overlap is done in two steps. In the first step preliminary design of arbor and sleeve overlap is calculated using a computer program based on a classic theory.

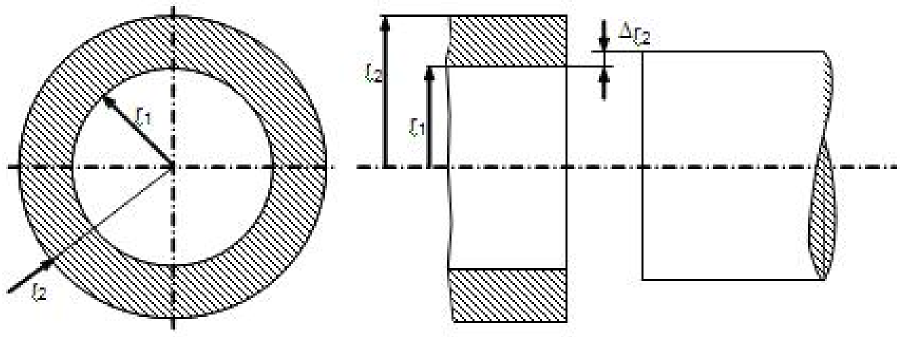

Fig. 1: Dimensions of sleeve and arbor

Normal pressure can be calculated, considering only elastic behaviour:

$$p_{con} = \frac{E(d_2^2 - d_1^2)}{d_1 d_2^2} \Delta r \qquad (1)$$

(p_{con} - normal pressure in contact area, E - young modulus, Δr – overlap, d_1- inner diameter of the sleeve, d_2 - outer diameter of the sleeve).

Radial and tangential stress due to shrink fit:

$$\sigma_r = C_1 - \frac{C_2}{r^2} \quad (2), \qquad \sigma_t = C_1 + \frac{C_2}{r^2} \quad (3),$$

where $$C_1 = p_{con} \frac{r_1^2}{r_2^2 - r_1^2} \quad (4), \qquad C_2 = p_{con} \frac{r_1^2 r_2^2}{r_2^2 - r_1^2} \quad (5),$$

(σr - radial stress, σt - circumferential (tangential) stress,C_1, C_2 - constants, r_1 - inner radius of the sleeve, r_2 - outer radius of the sleeve).

In the second step a detailed stress/strain analysis using finite element method is performed. The stresses are finally checked for fatigue. Following phenomena are considered:

- Shrink pressure and stress concentrations,
- Stresses due to non-stationary temperature regimes,
- Residual stresses in sleeve after thermal treatment,
- Axial stresses,
- Contact (hertzian) stress.

2.1 Temperature Field in Sleeved Roll

The aim of the analysis is to find the temperatures in sleeved rolls and to determine extreme differences in pressure between sleeve and arbor. The pressure drops most at the beginning of the hot rolling with cold WR and rises by intensive cooling of hot rolls.

For thermal calculation a proper estimation of heat transfer coefficient is necessary to obtain realistic temperature field. Measured temperatures on the roll surface have been used to obtain relevant heat transfer coefficients (HTC) by an inverse method.

In Fig. 2 there are computed temperature differences between selected points in arbor and sleeve at the beginning of the campaign of WRs. The max. difference corresponding to max. drop in shrink pressure is after 20 minutes of rolling (WR diameter 800 mm).

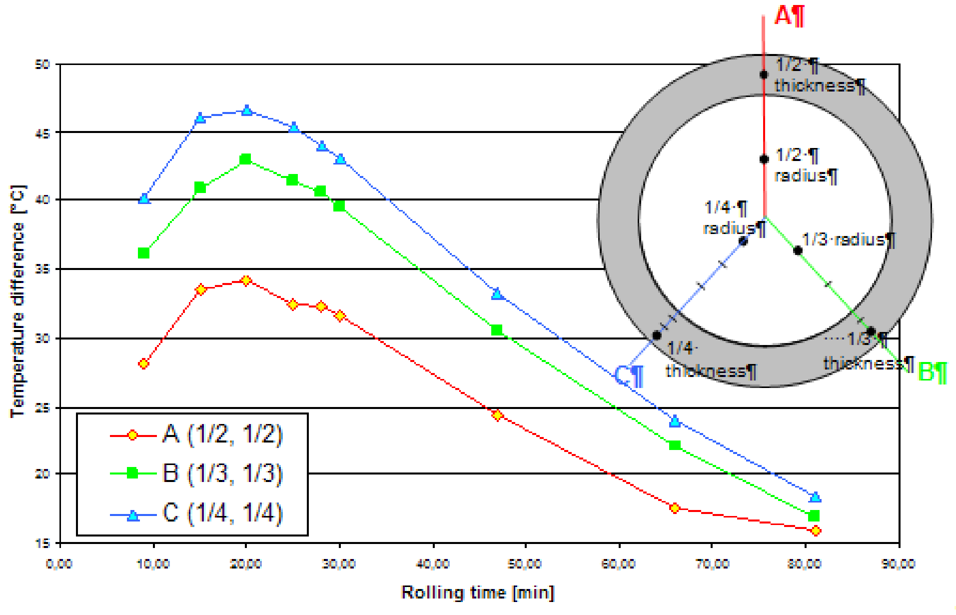

Fig. 2: Temperature difference between arbor and sleeve

2.2 Stresses Due to Shrink Fit and Stress Raisers

The equation (1) describes pressure between sleeve and arbor in central part, where both parts are cylindrical. At the edges or in conical parts FEM should be used to detect stress raisers (Fig.). Stress concentrations on the edge of the sleeve can be reduced by proper chamfers of the arbor.

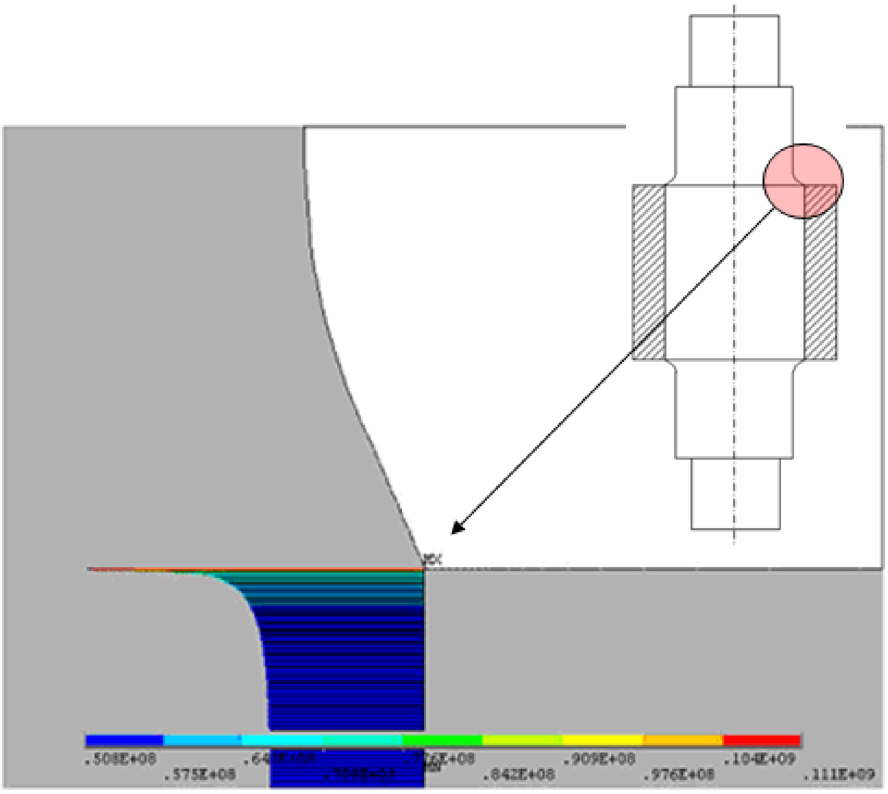

Fig. 3: Stress raiser – end of the sleeve

2.3 Axial Stress

During the shrink fitting, the sleeve cools down faster at the ends, so that the sleeve tends to grip the arbor earlier at both ends. That leads to tensile stress in the sleeve. This may cause cracking of the sleeve during rolling. Especially in long and thin-walled sleeves a very high level of axial tensile stress can be generated. To reduce the stress a special form of the arbor has been developed (Fig.). This form, together with controlled heating and cooling in process of shrinking, can reduce the dangerous stresses considerably. Other positive feature of the conical releases in arbor is a reduction of circumferential stresses on the roll edges, where maximum contact pressure between WR and BuR can be observed. Lower level of tensile stress means less danger of cracking.

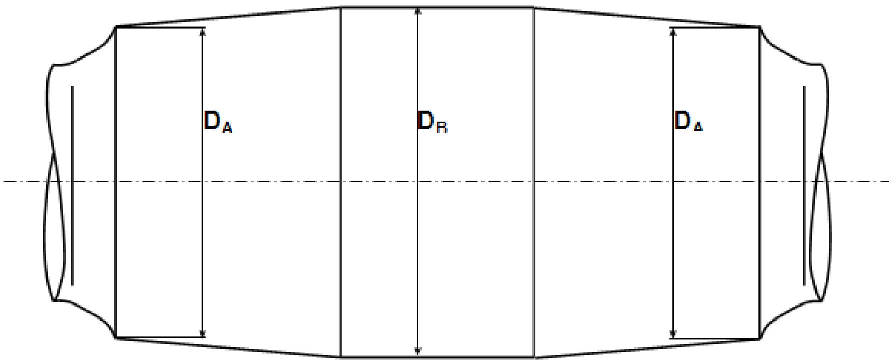

Fig. 4: Contact surface of the arbor with reliefs on both sides

2.4 A Contact Stress between BuR and WR

A contact stress between work rolls and backup rolls is one of the most important factors (Fig.) that can indirectly lead to sleeve fracture. If the contact pressure is too high, micro-cracks can originate in the places of maximal stresses under the surface (5 - 10mm). They act as stress raisers and may lead to crack propagation through the whole sleeve. For this reason contact stress should be taken into a great consideration. If sharp peaks of contact pressure exist on both ends of a roll barrel contact pressure should be redistributed by suitable chamfers and by positive grinding of BuRs. Fig. 6 demonstrates an influence of positive grinding of BuRs on contact pressure distribution. There were three pairs of grinding analysed (both for BuR and WR) that produce the same strip crown.

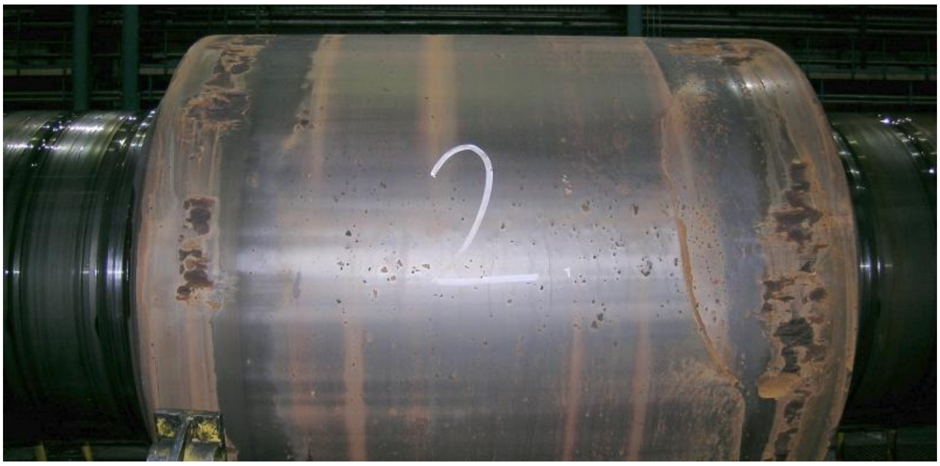

Fig. 5: Damaged BuR due to high contact pressure

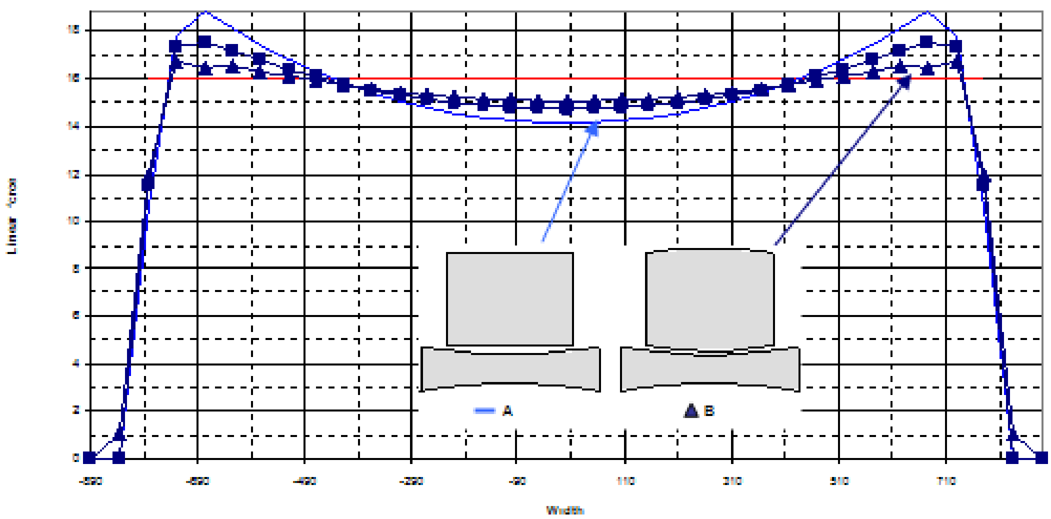

Fig. 6: Contact load distribution between WR and BuR for various grindings: WR-120µm, BR 0µm (without markers), WR-135µm, BR +50µm (squares), WR-140µm, BR +80µm (triangular markers)

Proper chamfers on BuRs are very important as well. Detailed analysis based on 3D FEM and following optimization of chamfer form helped to reduce the maximum stresses considerably (Fig. 7).

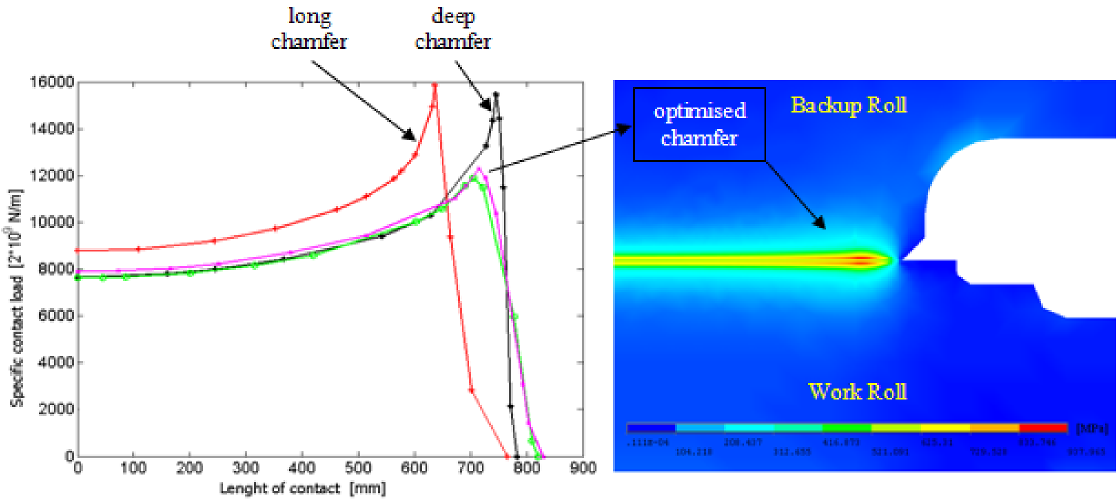

Fig. 7: Contact load between WR and BuR (left), distribution of HMH stresses

2.5 Residual Stresses after Thermal Treatment

It is obvious that residual stresses in the sleeve can influence the service life of the sleeved roll. But it is rather complicated to obtain the information about residual stresses both by experimental methods and computer simulation. Drilling method has been used to estimate residual stress in thin surface layer (1.5 mm) in three spots on the surface of a new BuR. The level of tangential stresses is negative and comparatively high.

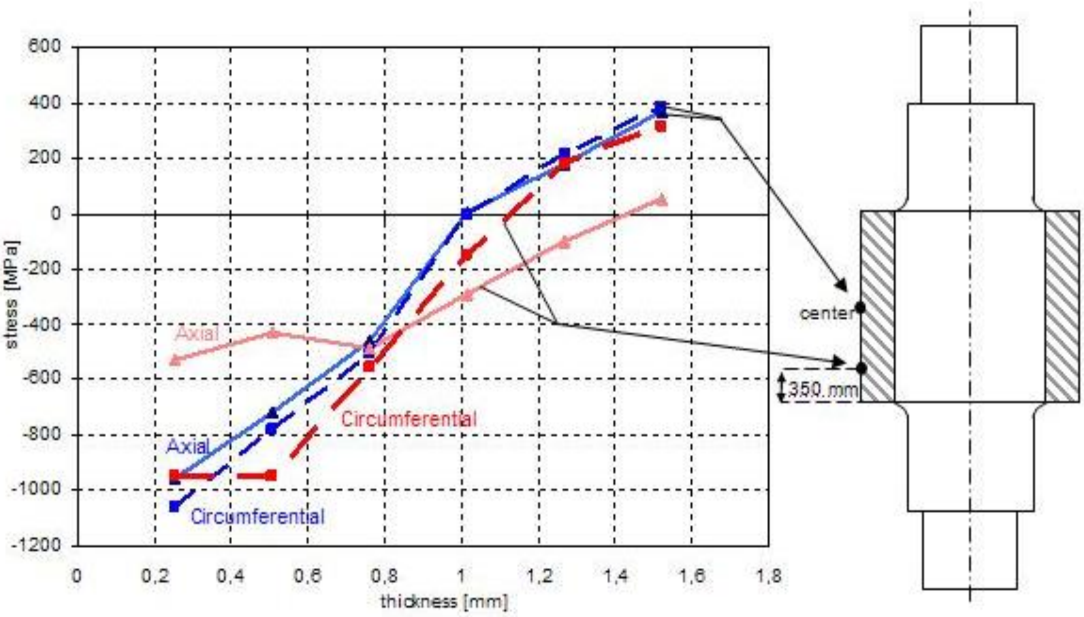

Fig. 8: Measured residual stresses (in 2 points) under the surface of the sleeve

A computer simulation considered only stresses generated due to temperature fields in the sleeve during thermal treatment. No volumetric changes caused by austenite decomposition were considered. The results showed that there exist regions under the surface of the sleeve with high negative stresses. The level of computed circumferential and axial stresses near the surface is slightly lower (25%) than measured ones. This might be caused by lower yield stress (1100Mpa) in computer simulation than in reality (1300 MPa).

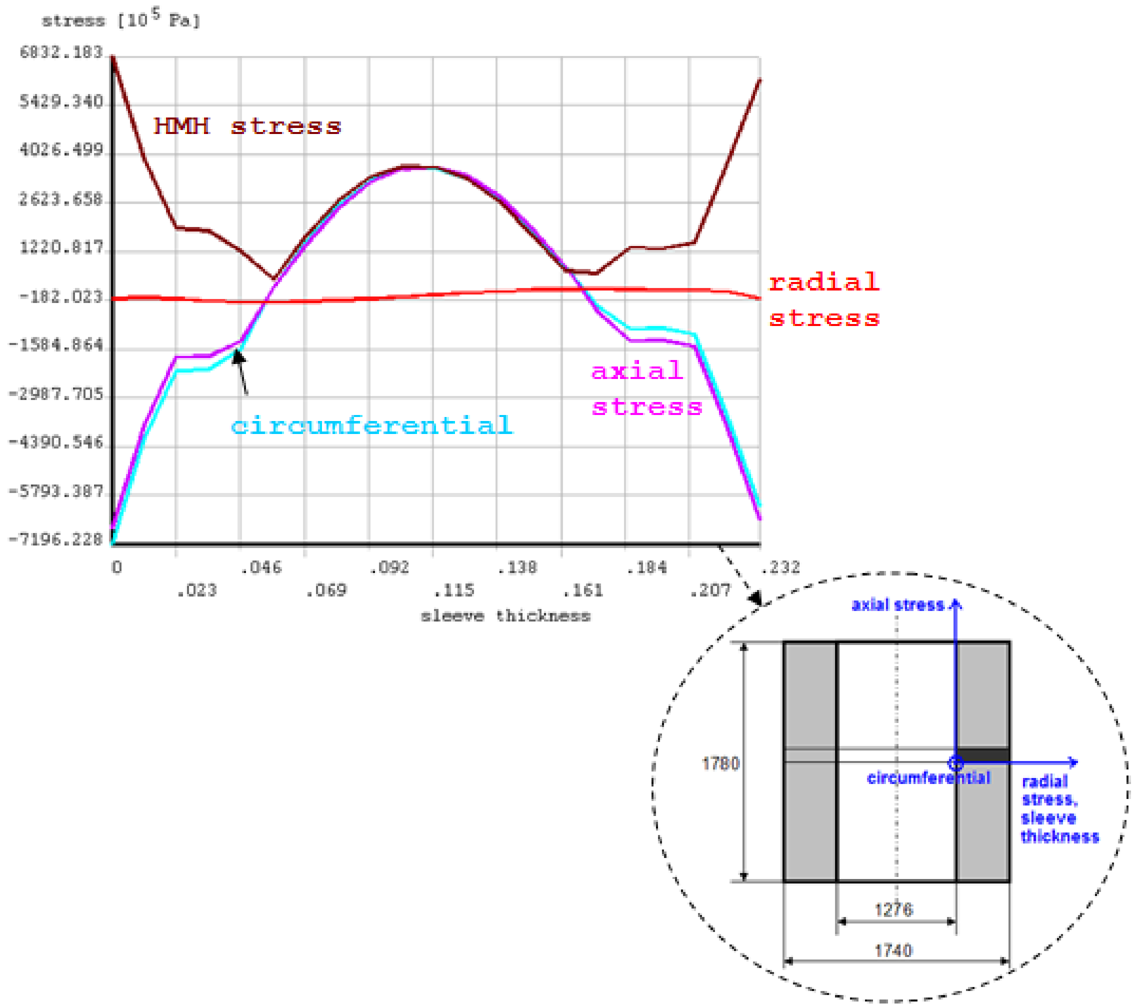

Fig. 9: Computed distribution of residual stresses in the sleeve

Fatigue Analysis

All stresses that are present in the sleeve are finally checked for fatigue. If very short service life is computed, smaller overlap is considered and checked for slipping and the whole analysis is repeated.

3. RECOMMENDED MEASURES TO PREVENT FRACTURE OF SLEEVES

- Removing of the damaged layer of the sleeve surface, where cracks have been initiated. The depth of the layer to remove by grinding should be specified by non-destructive testing (e.g. Lismar). After grinding the sleeve must not contain any cracks or other damages.
- More frequent grinding (shortening of roll campaign). This is not very popular measure. If other measures are not efficient the shortening of roll campaign can prevent the roll from fracture.
- Optimization of backup roll chamfers. Optimal chamfer can reduce the contact stress considerably. If rolls are frequently damaged at barrel edges, the form of chamfers should be carefully analysed. Very deep chamfers may cause higher peaks of contact pressure. On the other hand very long chamfers can lead to a non-stable rolling of narrow strips.
- Positive backup roll grinding. Positive BuR grinding reduces hertzian pressure on the edges of backup rolls especially in wide strips. Positive grinding of BuRs helps to reduce peaks of pressure by distributing the load. Excessive positive grinding of BuRs may lead to destabilisation of rolling in narrow strips.

4. EXPERIENCE WITH SLEEVED ROLLS

Sleeved rolls have been delivered and tested in several rolling mills in Czech Republic – Aluminium hot rolling mill (AlInvest), Cooper mill (Kovohutě Rokycany) and Hot Strip Mill (Arcelormittal Ostrava). Sleeved BuRs delivered for HSM 1500 mm (Arcelormittal Ostrava) are the most stressed rolls (roll diameter max/min 1740/1600 mm, barel length 1780 mm, max. separated force 30MN). Sleeves were forged either from older backup rolls or from new material. Four backup rolls have been delivered by Devimex Ltd in cooperation with Vitkovice Heavy Machinery. The first roll has produced over 1 000 000 tons (this is more than 100% of an average performance of solid backup rolls), the second one over 750 000 tons of strip (nearly 80% of an average performance). The second pair was delivered in 2008, both rolls are being used without any problems or limitations.

Rolls are carefully checked before each grinding using Lismar non-destructive testing. If defects are detected, the entire damaged layer is removed.

5. CONCLUSION

Sleeving rolls as a method of repair or renovation proves to be very cost effective, especially if the arbor is used twice or more times.

The handicap of sleeved rolls – permanent tensile stress present in the sleeve - can be eliminated by careful design with optimization of the form of arbor and overlap of the sleeve. Very important is the shrink fitting operation with controlled heating and cooling of the sleeve. Carefully designed and manufactured sleeved rolls proved to be equivalent to solid rolls in terms of rolled kilometers and tonnage.

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A LIST OF FIGURE CAPTIONS