DESIGN CRITERIA FOR ROLLING CONTACT FATIGUE RESISTANCE IN BACK-UP ROLLS

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ABSTRACT

The research presented in this work centres on surface initiated damage on back-up rolls whereby rolling contact fatigue cracks can propagate into the rolls potentially reaching the internal stress fields and leading to catastrophic failure and has sought to establish design criteria for avoiding such failures. The project objectives have been achieved by examining field evidence, determining the loading and tribological conditions at the work roll/back-up roll interface and investigating both theoretically and experimentally the mechanisms involved in rolling contact fatigue in this case. The presented rolling contact, fatigue and fracture mechanics model includes criteria for crack branching either upwards (i.e., relative safety) or downwards (i.e., potentially catastrophic) and the link between these two cases is related, quantitatively, to the properties of the roll material.

After linking mechanics to microstructure, the influence of work roll test disc surface roughness on both the surface wear of and the interaction between wear and rolling contact fatigue at the surface of back-up roll test discs has been quantified using the results obtained from experimental simulations carried out on a rolling-sliding testing machine. Finally practical quantitative recommendations are made for the mechanical and microstructural design of bainitic back-up roll materials, back-up roll redressing procedures and the surface roughness of both work rolls and back-up rolls presented to the mill.

INTRODUCTION

Demands in the steel industry for longer rolling campaigns, smaller roll inventories, lower roll maintenance costs and the rolling of ever thinner gauges, particularly on hot strip mills, have placed heavier duties on back-up rolls. This has increased the possibility of catastrophic failure due to rolling contact fatigue. Past approaches to improving back-up roll design have been based primarily on a combination of experience, available empirical data and trial and error. Roll metallurgy changes, both compositional and microstructural are proposed and trials on the mill are used to assess them. This approach is both time consuming and expensive.

From recent research work, material presented by several authors [1-6] based on extensive field evidence and the results of laboratory tests indicates that rolling contact fatigue cracks initiate both at the surface and subsurface. However in the absence of significant subsurface defects, there is no consensus on the causes of crack initiation or the mechanisms which propagate the cracks. There is also no clear definition of what constitutes rolling contact fatigue in this case. Nayak and Paul [1] suggest that cracks initiate subsurface at points of maximum shear stress and Tait [2] suggests that micro-fissures may initiate at the bottom of the work hardened surface layer. In contrast Kapadia and Marsden [3] concluded that,

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although in fatigue test specimens cracks initiated at microstructural imperfections, in practice, most spalling failures result from cracks initiated at the surface due to mill incidents and non-uniform contact pressures. Ohkomori et al. [4] also concluded that cracks are initiated at the surface, as a result of large localised contact stresses applied at each contact pass or due to the thermal shock arising from mill incidents.

Importantly, Ohkomori et al. [4] and Easter [6] found that back-up roll fatigue life increased with material hardness. However because of the strong possibility of surface damage to back-up rolls, which may lead to the creation of critical surface flaws, it is dangerous to use hardness as the main criterion for material design without considering the influence of yield stress and toughness and also the effective grain size, microstructural anisotropy and crystallographic texture of the material.

Based on the material presented by the above authors and, in particular, a schematic spalling failure model, Figure 1 (after [3]), the work presented here has aimed at a different approach, that is, to develop an understanding of the requirements for the roll material, specify these to dictate the required mechanical properties and finally link the mechanics to the required microstructure for the roll material.

**BACK-UP ROLL FAILURE**

**Field evidence**

Kapadia and Marsden [3] and Ohkomori et al. [4] present ample evidence of surface cracking on back-up rolls arising from roll slip, thermal shock and rolling contact fatigue, while Tait [2] shows a spall near the edge of a back-up roll barrel where a large fragment of material has been exfoliated from the surface. Frolish et al. [7] present a section of a sample of spalled material from a back-up roll, Figure 2. This section taken near the crack mouth (though not the point of crack initiation), shows evidence of an inclined surface crack which has propagated at a shallow angle to a length of approximately 2 mm, before turning down sharply to penetrate into the deeper substrate of the roll barrel. No evidence was seen of an up-turning crack.

It was assumed that the stresses, that initiate and propagate rolling contact fatigue cracks, arise from the action of the normal and tangential tractions acting at the work roll/back-up roll interface, the presence of surface asperities and the pressurisation and lubrication of the crack faces by the roll coolant. An example of how the presence of surface asperities within the contact region, coupled with the applied loads, could give rise to high asperity stresses which are superposed on the smooth body principal shear stresses (normalised by the maximum contact pressure $p_0$) is shown in Figure 3 (after Bailey and Sayles [8], for demonstration purposes only).

For the purposes of the development of the failure models and the establishment of the programme of experimental simulations, the possible responses of the roll material to the applied stresses were categorised as shown in Figure 4 (after Johnson [9]). For both the modelling and the required experimental simulations the parameters were chosen to predict and examine the rolling contact fatigue performance under the loading conditions described in categories 1 and 3, Figure 4.
METHODOLOGIES

Work roll/back-up roll loading profiles

The accurate determination of loading profiles is difficult and very little verifiable quantitative information is available. With the co-operation and permission of our industrial partners detailed mill and roll schedule information was obtained and with other relevant operating information was processed using an iterative hot strip profile coupled beam computer model. This proprietary software which takes account of all the important system variables except non-parallel back-up rolls has been developed by VAI Industries (UK) Ltd and was used to produce the representative work roll/back-up roll interface loading profiles. The maximum value of interface load, shown in Figure 5 (12000 N/mm), was the highest obtained in the analyses and has been used as the basis for determining the maximum contact pressure (1500 MPa) used in the experimental simulations and mathematical modelling.

Back-up roll material fatigue crack growth rates

Kapadia and Marsden [3] present the results of a series of fatigue crack growth tests on several back-up steels with varying mechanical and microstructural properties. A schematic summary of these results for mode I crack propagation is shown in Figure 6 (after [3]). The range of possible mode I thresholds derived from this summary has been used for the prediction of crack morphology in this work.

Prediction of crack morphology

Qualitative and quantitative models for the prediction of crack morphology ie., in the early part of phase 2, Figure 1 for a test disc pair and a work roll/back-up roll pair have been previously presented by Beynon and Frolish [10] and Frolish et al. [7] respectively. The crack propagation mechanisms are driven by various combinations of the asperity stresses, normal and tangential stresses and also by the lubrication and pressurisation of the crack faces. The predicted direction of early mode I crack propagation has been assumed to be in the direction of the calculated maximum mode I stress intensity factor $K_{\text{max\,th}}$ at the crack tip for the crack length at which a chosen mode I threshold would occur. The predicted crack morphologies for the case of a back-up roll, together with a summary of the crack propagation mechanisms, are shown in Figure 7.

Experimental simulation

The rolling contact fatigue and wear performances of a back-up roll steel were investigated during experimental simulations on the “SUROS” rolling-sliding testing machine at the University of Sheffield. The operation and capabilities of this machine are described in detail by Fletcher and Beynon [11]. The work roll test discs and back-up roll test discs used in the simulations were manufactured from high-speed steel (hardness 830 Hv) and a cast bainitic steel (hardness 480 Hv) respectively. The nominal outer circumference and track width of both sets of test discs were 173 and 10 mm respectively.

The morphology of a typical crack produced in back-up roll test discs is shown in Figure 8 (the largest observed cracks commenced propagation in a direction at 60° to the surface normal). The observed crack morphologies coupled with evidence shown in Figure 2 were used to validate the predictions of the failure models and link crack propagation to the...
details of the bainitic steel microstructure and in particular the size and nature of the
 carbide/ferrite boundaries and the dimensions of the ferrite packets.

The wear tests were carried out using work roll test discs with surface roughnesses lying
within the range Ra 0.1 µm to Ra 0.75 µm. This range is similar to that given by Caithness
et al. [12] for high-speed steel work rolls entering service in the former BSFP hot strip mill
at Llanwern, UK. The results of these tests showing the influence of work roll disc surface
roughness on the wear performance of the back-up roll test discs and the interaction between
wear and rolling contact fatigue in this case are shown in Figures 9 and 10 respectively.

DESIGN CRITERIA

Modelling and testing of back-up roll materials

The modelling of failure in rolling contact and testing of wear and rolling contact fatigue
performance of back-up roll materials should be carried out assuming a maximum contact
pressure of 1500 MPa, operating conditions of -1% slip (work roll driving back-up roll) and
water lubrication, and with the roughness of the ground finish on the work roll test disc
counter-face lying in the range Ra 0.3 µm to Ra 0.4 µm.

Material design

The processing route for the manufacture of bainitic back-up roll steels should aim to
produce a tempered lower bainitic steel microstructure. The length of the carbide/ferrite
packet boundaries should be limited by controlling prior austenite grains size

Yoder et al. [13] found that for a range of steel types, propagation of fatigue cracks in mode
I commences when the cyclic plastic zone size at the crack tip is the same as the mean
effective grain size of the material. If this assumption is made then, coupled with
calculations for the approximate cyclic plastic zone sizes at the crack tips in this case, an
expression can be obtained for the value of the maximum mode I stress intensity factor at
threshold $K_{\text{max}, \text{th}}$ in terms of the yield stress of the material $\sigma_y$ and the mean effective grain
size $\bar{d}$. Examination of this expression indicates that the highest possible mode I threshold
should be obtained by maximising the mechanical and microstructural parameter $\sigma_y \sqrt{\bar{d}}$.
Identification of high angle grain boundaries by electron backscattered diffraction
microscopy indicates that $\bar{d}$ should be taken as the smallest dimension of the ferrite packets.

In the outer shell of the back-up roll barrel the volume fraction of second phases of pearlite,
retained austenite and martensite should be kept to a minimum.

Roll maintenance

The results obtained from the experimental simulations using test disc specimens indicated
that, for an optimum balance between wear and rolling contact fatigue, the ground finish on
the surface of redressed work rolls should lie in the range Ra 0.3 µm to Ra 0.4 µm. Where
practical the roughness of the ground surface on re-dressed back-up rolls should be similar
to that on work rolls.
Examination of the predicted crack morphologies for back-up rolls (Figure 7) indicates that, for materials where the maximum mode I stress intensity factor at threshold is in the range presented by Kapadia and Marsden [3] and under conditions of crack pressurisation, early mode I crack propagation is predicted to be close to the direction of the inclined shear crack. Continued propagation should therefore cause the crack to be up-turning and the maximum depth of crack penetration should be less than 0.7 mm. To ensure the removal of such cracks, the diametral amount of material removed during re-dressing should be 2 mm.

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REFERENCES

Figure 1. Schematic model for five stages of spalling failure (after [3])

1. Surface bruise or crack
2. Formation of fatigue band
3. Propagation of fatigue band
4. Rapid (unstable) crack growth
5. Spall

Figure 2. Sample taken from spalled material from a back-up roll, polished and etched [7]
Figure 3. Principal shear stresses with surface roughness and sliding friction (after [8]), where, $x$ = distance from centre of contact, $z$ = depth below surface, $b$ = half contact width, $p_{(x)}$ = normal traction and $q_{(x)}$ = tangential traction.

Figure 4. Material response to cyclic loading (after [9]).

(1) Perfectly elastic
(2) Elastic shakedown
(3) Cyclic plasticity (plastic shakedown)
(4) Incremental collapse (ratchetting)
Figure 5. Work roll/back-up roll interface loading profile with wear trapezium applied to work roll

Figure 6. Mode I fatigue crack growth rates for back-up roll steels (after [3])
Figure 7. Schematic diagram of the predicted crack morphologies for inclined surface initiated cracks in a back-up roll as the mode I threshold of the material is increased and where the early propagation by the shear mechanism is in a direction at 60° to the surface normal. Mode I (tensile mode) results are shown for crack lengths of (c) 200 µm, (d) 350 µm, (e) 500 µm, (f) 750 µm and (g) 1200 µm.

Figure 8. Surface initiated rolling contact fatigue crack produced in a test disc specimen under simulated operating conditions.
Figure 9. Laboratory wear results (SUROS testing machine, maximum contact pressure 1500 MPa, -1% slip, water lubricated) showing the influence of work roll test disc test track surface roughness on the wear performance of back-up roll test disc surfaces. *Range of ground finishes on the surface of HSS work rolls entering service at the former BSSP Llanwern Hot Strip Finishing Mill, Caithness at al. [12].

Figure 10. Wear and rolling contact fatigue results obtained from experimental simulations carried to rolling contact failure ($F^*$), as indicated by the crack detection system. (SUROS testing machine, maximum contact pressure 1500 MPa, -1% slip, water lubricated). Surface roughness on work roll test disc track measured in $\mu$m.