Investigations into Roll Thermal Fatigue in Hot Rolling

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ABSTRACT: In the current paper, a study into the mechanism of roll thermal fatigue crack propagation during hot rolling of long products is presented. A range of 2D implicit FEM models taking into account the complex thermal and mechanical interactions during rolling and cyclic cooling have been developed and used to predict how the stress state inside the roll contributes in a different manner to energy release at the crack tip, depending on the length of the initial crack. A stress intensity factor (SIF) approach has been used to derive the crack growth rate for a given roll material and roll cooling configuration. This work describes the methodology of predicting thermal fatigue crack growth using innovative modelling techniques and highlights the importance one needs to attach to operating conditions (roll cooling, roll coating, controlling oxide scale etc.) alongside the optimum selection of roll material for reduced surface degradation of current hot long product rolls.

Key words: hot rolling, thermal fatigue, roll cooling, crack propagation, J integral

1 INTRODUCTION

Rolls during hot rolling are subjected to cyclic thermal variations, which, depending on the mill operating conditions (position in the mill, rolling schedule) may induce severe thermal gradients. The developed thermal stresses add to already existing internal tensile residual stresses (from casting for a cast roll or shrink fit for sleeved roll). If undetected, the resulting fire cracking on the surface ("fire crazing") can lead ultimately to roll breakage, with costly consequences to mill production. In addition, any mill incidence, such as a stall ("cobble") can further contribute to a reduction in roll life. The current remedy practice of removing the outer surface layer (sometimes beyond the required dressing imposed by "normal" roll wear) amounts to production costs and may require an increase in roll stock.
Despite the considerable effort devoted, during the last decades, to study thermal fatigue phenomenon, it is recognised that in the case of hot rolling of long products there is a lack of understanding how, when and how fast thermal cracks advance with respect to rolling parameters. This is due to the complexity of processing factors (variations in roll heating/cooling regimes, complex contact areas, internal crack oxidation, lubrication-when used), as well as to the paucity of roll material data in the range of operating conditions. Most of the published results relate to steel rolls, such as high speed steel [1, 2, 3]. A general analytical approach to predict thermal crack growth for high/low thermal cycle was proposed by Malm and Nortrsom in 1979 [].
In the current paper, an investigative work into the mechanism of thermal fatigue crack propagation during a rolling cycle is presented using a FE modelling approach. It is shown how the stress state inside the roll contributes in a different manner to energy release at the crack tip, depending on the length of the initial crack.
A stress intensity factor (SIF) approach has been used to derive the crack growth rate for a given roll material and roll cooling configuration.
This work describes the methodology of predicting thermal fatigue crack growth using innovative modelling techniques and highlights the importance one needs to attach to operating conditions (roll cooling, roll coating, controlling oxide scale etc.) alongside the optimum selection of roll material for a better usage of the current rolls for hot rolling.

2 THERMAL CRACK MODELLING

2.1 FE model

A simplified 2D FE model of roll cooling (figure 1) has been used to simulate the effect of cyclic heating and cooling on four different predefined cracks. The hot feedstock was modelled as an equivalent heat source, which also exerts a mechanical pressure onto the roll. Heat transfer coefficient in the cooling area is calculated based on real cooling configuration (system geometry, nozzle type, water flow rate/pressure) using an in-house software package. The coupled thermo-mechanical FE analysis was carried out using the implicit Abaqus 6-6.1 version. A sufficient number of revolutions (depending on roll speed) are required to achieve a quasi steady state heat exchange regime, which can significantly increase the CPU time. This drawback can, however, be overcome by running a heat transfer analysis using a simpler 2D FE model (with no cracks) and importing the roll temperature gradient into the first model.

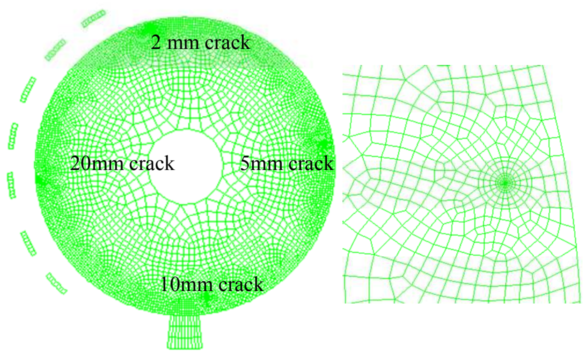

Fig. 1 The FE model with cracks used for analysis

A linear elastic roll material justified the application of LEFM concepts for extraction of J integrals at crack tips (as a measure of energy release rate). Paris law is then employed to relate the crack length to number of cycles, provided that roll material parameters are known. Using this approach, the FE model can simulate quantitatively the effect of various roll cooling and heating scenarios on thermal crack growth.

2.2 Effect of roll cooling intensity on energy release rate

As roll cooling is an independent and significant rolling process parameter that can be controlled in a mill environment within boundaries imposed by mill logistics (such as nozzle type, water flow pressure at main pipes, efficiency of filtering system for coolant recirculation etc.), the effect of roll cooling on thermal crack growth has been studied. Three different cooling scenarios have been simulated: “normal” regime (HTC=□0kW/m^{2}K), poor cooling (HTC=20kW/m^{2}K) and overcooling (HTC=100kW/m^{2}K). In the last case, a quasi steady state thermal regime, achieved under “normal” cooling is followed by a brusque increase in cooling intensity (due to, for instance, severe fluctuations in roll cooling intensity: sudden unblocking of some of the nozzles, mains pressure increase etc.). The effect of these cases on the amount of energy release rate is shown in figure 2.

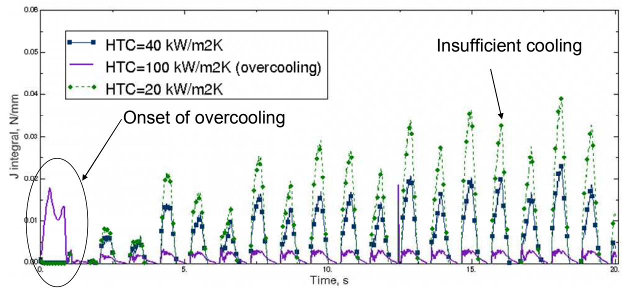

Fig. 2 Effect of roll intensity on J integral at thermal crack tip (initial roll temperature: 30^{0}C, roll speed: 6 rad/s, feedstock temperature: 1100^{0}C, roll diameter: 360 mm)

It can be noticed that an “optimum” cooling regime assures a quasi constant variation of J integral, which results in a similar effect on the thermal crack growth rate. On contrary, as expected, an insufficient roll cooling results in continuously increasing rate of energy release at crack tip (resulting in an accelerated growth). As this phenomenon is proportional to the roll surface temperature variation (measurable), methods to control roll thermal fatigue can thus be developed and applied. A slightly more complicated case can occur in practice when excessive roll cooling is applied suddenly on a hot roll. The initial thermal shock results in a severe and- most importantly- over a long time interval of the energy release rate at the crack tip. It is interesting to know what the effect on the roll’s microstructure this prolonged state of stress might have, so that superior materials could be developed.

2.3 Analysis of thermal crack growth over one cycle

Optimum roll cooling regime should ensure a constant thermal crown (roll heat affected zone, RHAZ), where the temperature fluctuates cyclically, the depth of which is dictated by the contact time with the hot feedstock via roll's thermal diffusivity.

<u>a. Shallow thermal cracks</u> (sometimes left over after roll regrinding or initiated around hard carbides/inclusions) within this thermal band are subjected to cyclic heat variations, exacerbated by the unequal thermal stresses on each side of the crack due to the inherent nature of the phenomena (i.e., one side is always hotter/cooler then the other one) in a steady state rolling thermal regime. As the FE model shows (figure 3), the hoop stresses within the RHAZ, due to only heat exchange and mechanical rolling, are compressive (ignoring shrink-fit or manufacturing residual stresses). Instead, the axial stresses (figure □), induced by the asymmetrical thermal gradient, seem to be the main parameter for roll thermal fatigue (steady state thermal conditions).

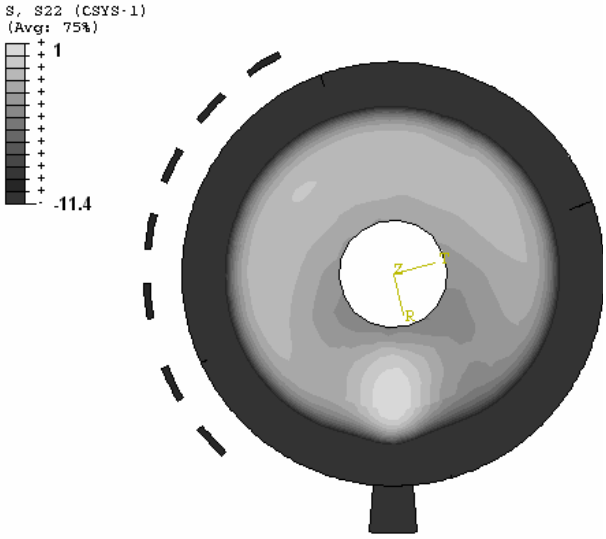

Fig. 3 Normalised hoop stress during thermal steady state hot rolling (residual stresses ignored)

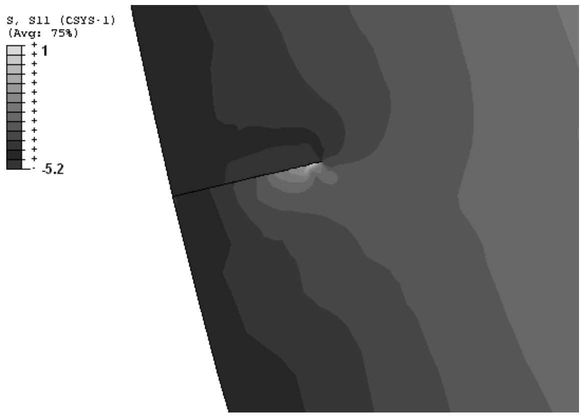

Fig. □Axial normalised stress (shallow crack in cooling area)

This corresponds to Mode II of crack surface displacement (sliding). Once the crack grows to a certain length, its tip can reach the high hoop tensile stress deeper below the surface (see figure 3) and Mode I (opening) complements Mode II. First mode can also occur in the case of insufficient cooling/mill incidence, high frictional force or high roll speed.

<u>b. Deep thermal cracks</u>, beyond the RHAZ, are mainly affected by the mechanical contact with the feedstock due to the contact pressure (Mode II). Their growth is therefore more influenced by pass reduction. The mixed thermal crack growth mechanism is sketched in figure 5.

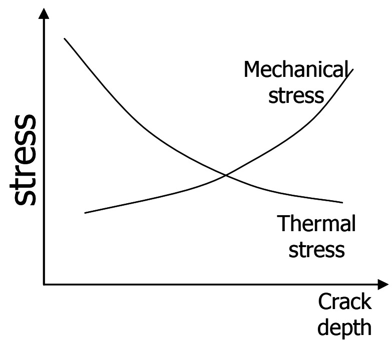

Fig. 5 Dual mechanism of thermal crack growth in hot rolling

Evolution of J integral for two thermal cracks over one cycle against roll surface temperature evolution near the crack is shown in figure 6. Maximum energy release rate for a "deep" crack takes place at entry to roll gap, whilst for a "shallow" crack, it is the cooling area, mainly beneath the first cooling nozzle, where energy release rate associated with crack growth take place. This observation can lead to optimisation of the roll cooling design, with the objective to reduce the severe thermal gradient between crack sides (i.e., ramping the heat extraction, whilst maintaining the RHAZ depth constant).

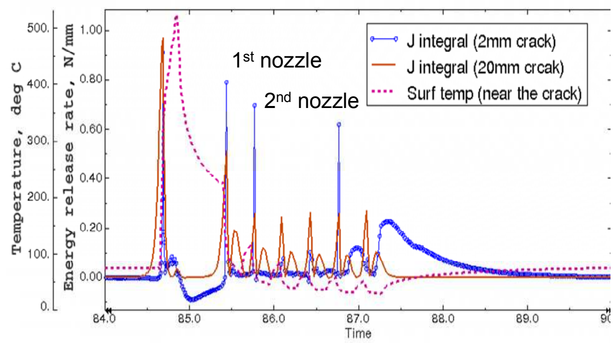

Fig. 6 J integral for a "shallow" (2mm) and a "deep" (20mm) thermal crack over one cycle vs. roll surface temperature near each of the cracks

2.4 Prediction of work roll thermal fatigue and roll life

Using the J integral (hence SIF) calculated from the FE model and assuming known roll material parameters Paris law can be used to calculate the number of cycles (for a given set of rolling/cooling parameters, under the assumption of linear crack growth regime) until a certain length of thermal crack is reached and roll returned to roll shop for redressing. An example of the capability of the proposed approach is shown in figure 7, where a roll cooling situation was simulated using two different roll materials (material 1 – high Cr and material 2 – Superten) in two different cooling scenarios: poor cooling, HTC=20kW/m^{2}K and more intense cooling, HTC=□5kW/m^{2}K. In addition to optimising roll cooling based on required HTC and available mill capacity, one can also assess the suitability of other roll materials for a given rolling stand. (Here, the indications are that more performance can be obtained from the second roll material if the same improvement in roll cooling was made.)

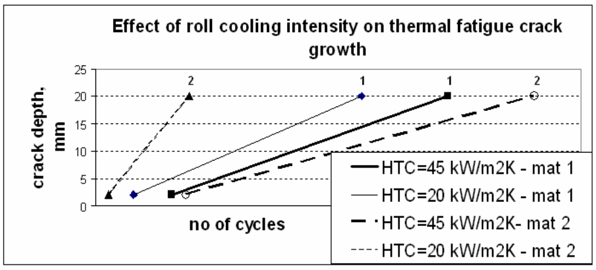

Fig. 7 Example of predicting thermal crack growth for two different roll materials under two different cooling regimes for the same rolling conditions

Controlling roll surface temperature by an optimum roll cooling is paramount in limiting the thermal crack growth. For instance, a numerical calculation shows that an increase of roll surface temperature of 16^{0}C can increase the rate of crack growth by a factor of 2.58.

3 CONCLUSIONS

An FE based method for investigating the mechanism of thermal crack growth has been proposed. Using the concepts of LEFM, estimations of roll life, from the perspective of thermal fatigue, can be developed. This can be further utilised to optimise roll cooling within the constraints of the mill, as well as the roll capability in service. More work is, however, needed to obtain material properties of current or prospective rolls at operational temperature.

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