Fracture Mechanics Approach of Repaired Top Roll Shafts in Sugar Cane Mills

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ABSTRACT

Several top roll shafts failed in service in different sugar mills. After analysis it was determined that the failures happened due to a fatigue process, where the cracks started at surface-located micro defects, caused by abrasive wear, machining marks or defects in the repair welds when applied. A research project to extend the life of top roll shafts with excessive wear and developing cracks was structured with the Mechanical Engineering School of Universidad del Valle (Cali – Colombia), CENICAÑA and Manuelita Mill. Failure locations and frequencies were documented together with materials, torque and crushing loads. A shaft journal on the drive side was chosen for detailed analysis because of the higher frequency of failures found there. Two options were considered to obtain a shaft free of cracks: the reduction of the journal diameter and the recovery of the original dimensions using arc welding procedures and consumables. A fracture mechanics approach was used to predict the maximum defect size tolerated in a repaired shaft and the time between non-destructive testing inspections. It was found that the reliability of a welded shaft can be impaired if a stress relieving process is not used: service life can be reduced by an estimated 63% because of residual stresses. A minimum diameter for a reduced size shaft was calculated, a 5% reduction reduces the required inspection intervals by 38%.

Keywords: mill shaft, fracture, welding.

INTRODUCTION

A cane crushing mill is a heavily loaded piece of machinery and because of function and design, top roll shafts are highly stressed components affected by juice and soil contamination. Several top roll shafts failed in service at Colombian sugar mills in a relatively short period of time and after analysis it was determined that the failures happened due to a fatigue process, where the cracks started at surface-located microdefects, caused by abrasive wear, machining marks or defects in the repair welds when applied.

From crack detection reports, in grade 1045 top roll shafts of a 84"x 43" tandem at Manuelita Sugar Mill, both frequency and location of cracks were identified. Figure 1 shows the results: 82 failed shafts were reported where 115 cracks were detected using Non Destructive Testing (NTD) methods. The highest percentage of defects (35 %) was located at journal shoulder close to the roll shell, on the drive side. Other researchers (Anderson and Loughran (1998), Reid (1989) have found similar results. Because of the high percentage of defects in this area, loads and stresses in the mentioned zone were considered in this study.

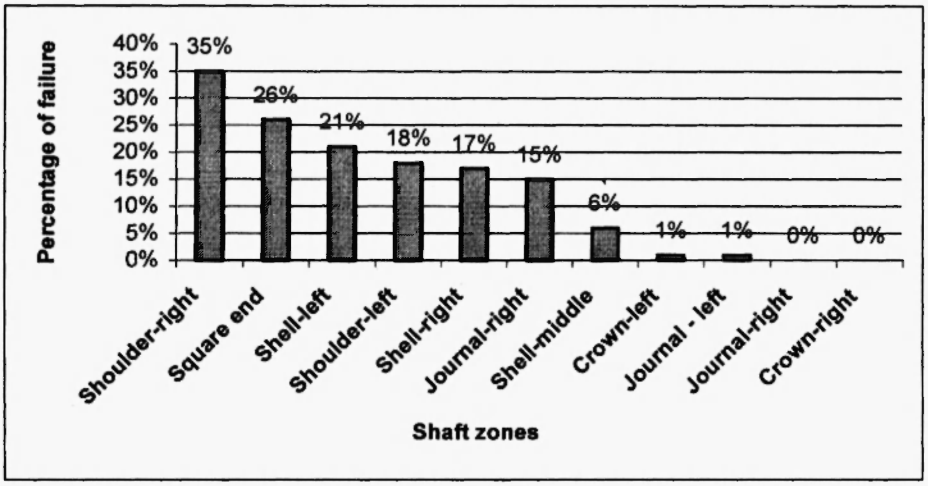


Fig. 1: Roll shaft cracks failure locations at Manuelita S.A. 1991-2003.

TYPES OF CRACKS IN THE MILL ROLL SHAFTS

Two crack models provide a reasonable math to the observed crack shapes (Arzola, 2003): the semi-elliptical superficial cracks, and the circumferential crack. Several semi-elliptical cracks can arise, in a given section of the shaft, at different times, and they can propagate until they become a circumferential crack when they coalesce, Figure 2 shows a fractured shaft section where different semi-elliptical cracks had propagated until they formed a circumferential crack. Also a circumferential crack can arise and propagate due to circumferential surface defects on shaft journal, for example, deep groove marks caused by the machining process or abrasive wear, caused by extraneous matter. Figure 3 shows some marks on the shaft surface journal surface.

Fig. 2: Several semi-elliptical cracks

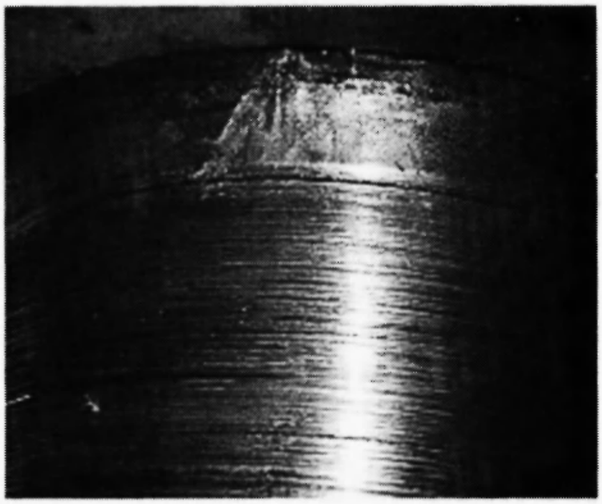


Fig. 3: Abrasive wear on the top roll shaft surface

MATERIAL ANALYSIS

Fracture toughness of steel used on roll shaft.

Standard Crack Tip Opening Displacement (CTOD) tests were performed on AISI1045 steel in order to determine fracture toughness. A device adapted to a universal milling machine was used to precrack specimens (Hinestrosa, 2004).

Rotating bending fatigue and juice corrosion synergy for 1045 steel.

Rotating bending fatigue and juice corrosion synergy for 1045 steel was considered (Gómez, 2004), using standard rotating fatigue specimens. Typical fourth mill degraded juice with a pH of 4 was used for the trials. During rotation a continuous flow of juice was also applied. Comparison between dry standard test and the adapted corrosion experiment showed a reduction of 15% in the fatigue limit, Sn'. This result could be applicable for zones not protected by the presence of lubricant. In the analysis of the journal shoulder discussed later in this paper, a reduction of fatigue life due to corrosion effect was not considered.

Typical arc welded metallography analysis

A welding-recovered shaft was analyzed to study causes of fracture. A welding deposit with an austenoferrític structure is shown in Figure 4, where the dendrites formation is observed clearly. In Figure 5, a crack is shown in the interface between the base metal and the weld metal, coming up from a superficial defect probably created by a wrong welding procedure. A lack of fusion was clearly observed in Figure 6, allowing a selective crack development direction. The interface between the ferritic- perlitic base and austeno-ferritic weld metal is presented in Figure 7.

Fig. 4: Recovered welding.

Fig. 5: Cracks in recovered welding.

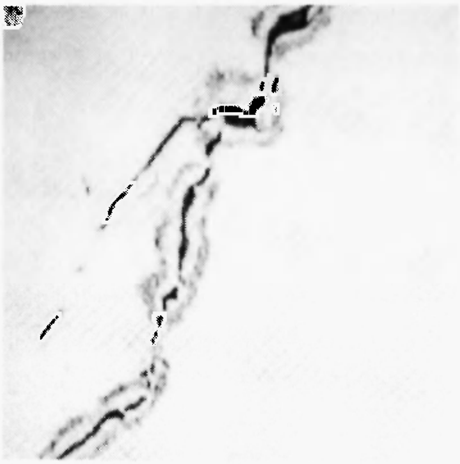


Fig. 6: Welding defect.

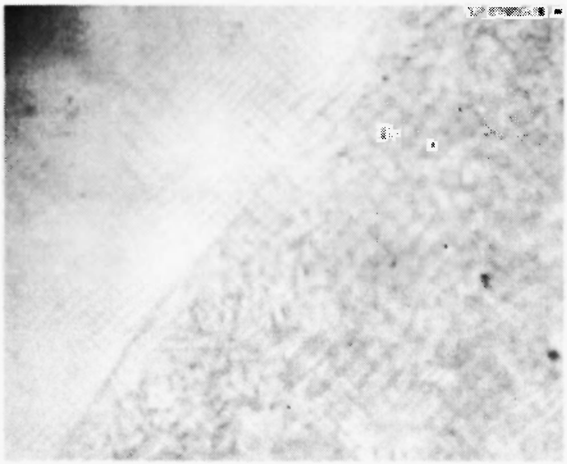


Fig. 7: Base metal and welding interface.

LOADS ON A ROLL SHAFT

Journal loads and stresses vary with roll lift and milling torque. Roll lift provides an approximately constant load system but torque sharing inside the mill is a complex process. Torque and load recordings for a shaft with a 19" x 26" journal were taken (Rodriguez, 2004) to establish load levels and the fractions of time corresponding to those load levels. The shaft material was 1045. A history of the radial force generated in the squared end of a top roll shaft because of the bending moment induced by a square coupling was estimated from the measured torque using the work of Ókamura H. *et al.* (1972); Figure 8 shows the estimated history.

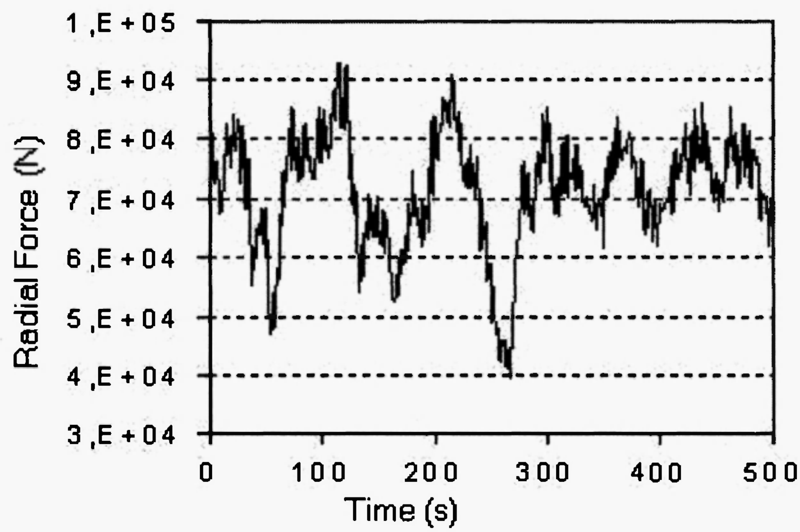


Fig. 8: Estimated radial force in shaft squared end from real torque measurements.

Five representative levels of radial force and the associate information were determined. Table 1 shows levels and the corresponding fractions of time as well as the torque and lift information. The general stress state of a top roll shaft was then calculated using all internal loads and a typical load sharing among rolls. Table 2 shows shear forces, bending moments in x-z planes and twist moments on journal shaft.

Table 1

Radial forces on squared end.

Load state	Radial force (KN)	Data number	Percentage of time	Torque (KN-m)	Lift (m)
No 1	334	544	19	896.03	0.0068
No 2	357	753	26	955.54	0.0074
No 3	379	693	24	1013.86	0.0076
No 4	401	541	19	1072.91	0.0081
No 5	491	362	13	1273.04	0.0097

Table 2

Internal forces on journal shaft.

Load state	Vz (KN)	Mx (KN-m)	Vx (KN)	Mz (KN-m)	T (KN-m)
No 1	-2539.2	-250.4	331.9	-336.3	507.5
No 2	-2526.8	-203.2	367.5	-351.8	543.3
No 3	-2514.3	-156.3	401.6	-367.0	578.3
No 4	-2501.4	-108.3	435.3	-382.3	613.7
No 5	-3492.2	-2414.5	762.1	-364.7	731.2

CONSIDERATIONS OF REPAIR OF A SHAFT JOURNAL WITH EXCESSIVE WEAR OR CRACKS IN PROGRESS

Plastic zone size in the crack tip

The plastic zone (r_y) in the front of a crack must be eliminated in order to stop crack propagation. This plastic zone will always have a size that can be estimated according to the stress intensity factor (K) and the yield stress (σ_y). The size of the plastic zone under plane strain condition can be obtained as (Rolfe, 1977):

$$r_y = \frac{1}{6\cdot\pi}\left(\frac{K}{\sigma_y}\right)^2$$

Figures 9 and 10 show the plastic zone size for semielliptical and circumferential cracks respectively.

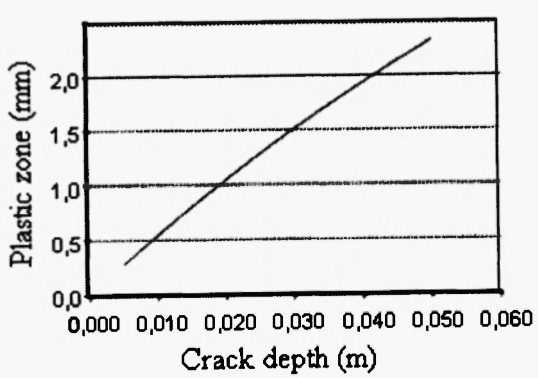


Fig. 9: Extension of the plastic zone for a semielliptical superficial crack in the journal shaft.

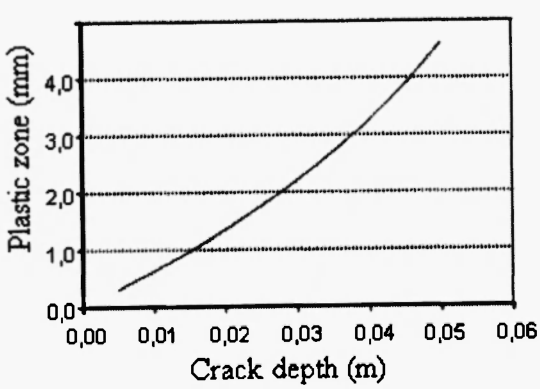


Fig. 10: Extension of the plastic zone for a circumferential crack in the journal shaft.

Using σ_y = 350 Mpa and the fracture toughness, Kic = 88 Mpam$^{1/2}$ (Arzola, 2003) in the equation a value of 3.35 mm was obtained as maximum size of the plastic zone under plane strain condition in the 1045 steel. Therefore in a recovery process a 3.35 mm zone first needs to be removed from the crack tip.

Journal diameter reduction

The load state was determined on the shaft, therefore the equivalent stresses were calculated. When a journal shaft presents heavy wear caused by high stress and contamination with extraneous matter, machining to a smaller diameter is an alternative for the shaft to continue working. One of the questions that must be resolved is what is the minimum diameter to which it is possible to take a top shaft before having to recover the original size using arc welding.

A smaller journal diameter raises nominal stresses as shown in Figure 11. The smaller diameter also increases the effect of the stress concentration caused by the change of section between the journal and the zone of shell landing as can be observed in Figure 12 where bending and torsion stress concentration factors both increase with a smaller diameter. The stress concentration factors were calculated according to diameter and fillet shaft. In this case the filled use was 5 inches.

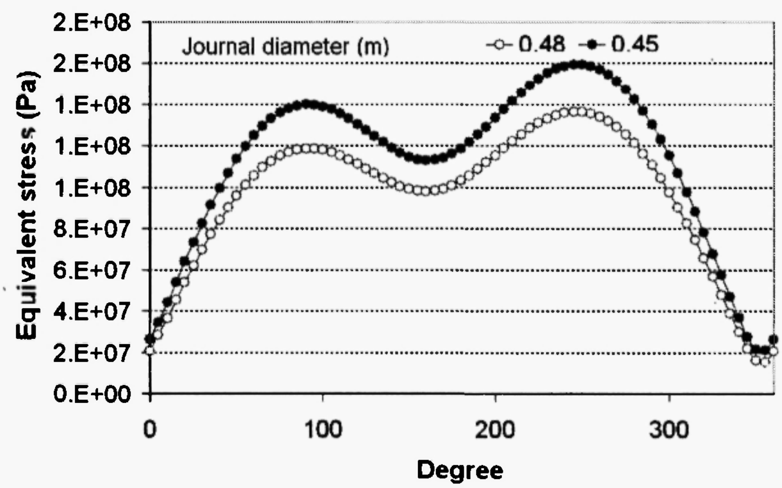
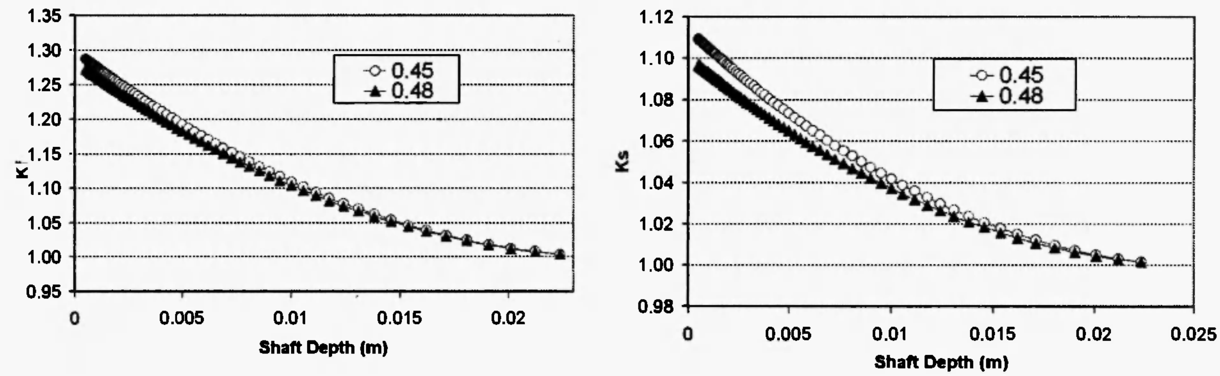


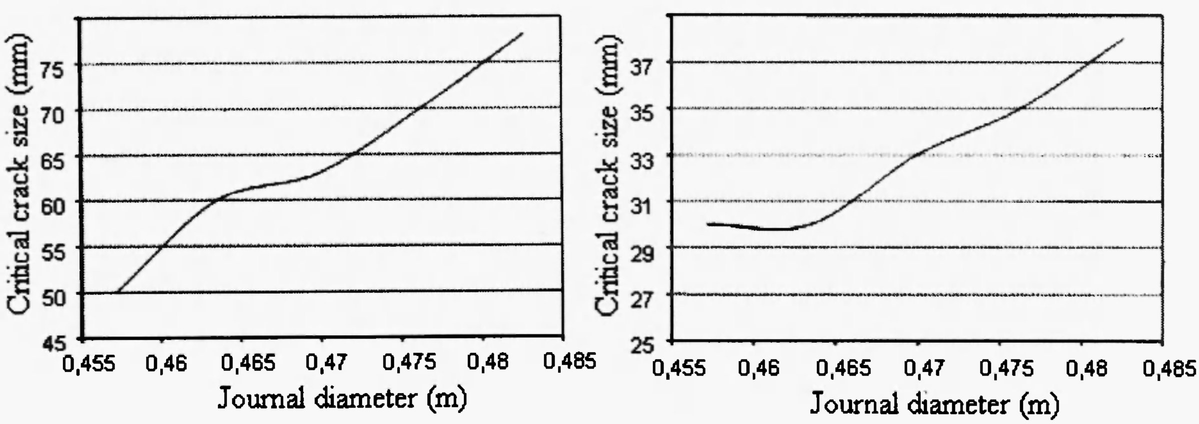
Fig. 11: Equivalent stresses in the journal for different diameters.

The critical crack size for semielliptical and circumferential cracks for different values of diameter can be seen in Figure 13. The critical crack size was determined using a maximum load that the shaft can support. The lift data were used to find the overload values.



Bending *Torsion*

Fig. 12: Stress concentration factors Kf and Ks for different journal diameters



Semielliptical crack

Circumferential crack

Fig. 13: Critical crack size for different diameters

The critical crack size cannot be used as a criterion for the determination of minimum feasible journal diameter. The minimum feasible journal diameter will depend on the time it takes for a crack of the minimum size to be detectable, to propagate up to the critical length. This time can be established using as a criterion the period between NDT inspections. Figure 14 shows a month as the preferred time between inspections of the evaluated top roll shaft with reduced diameter. This frequency is not practical so a more feasible time between NDT examinations will define the lowest diameter that must be used. The graphs were determined using an integration procedure to find the minimum time between inspections. A 5% reduction shaft journal reduces the required inspection intervals by 38%.

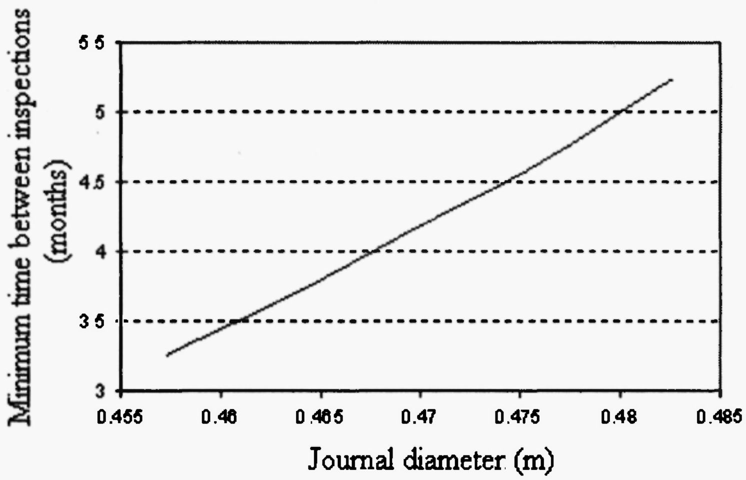


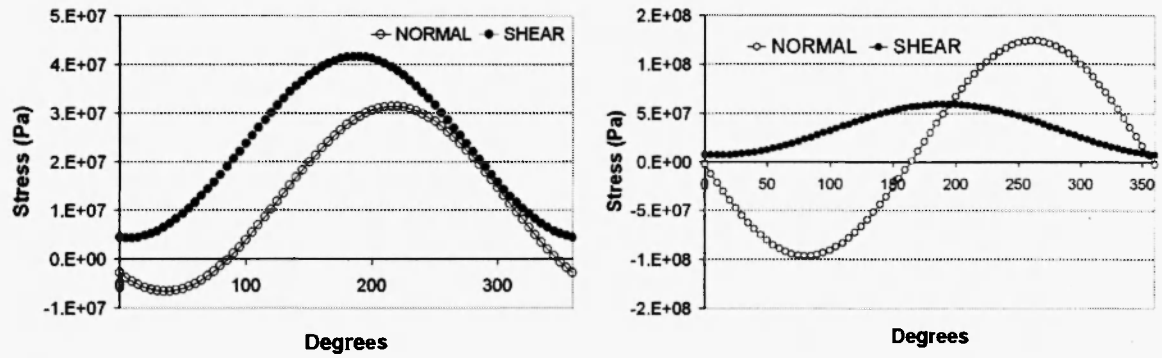
Fig 14: Minimum time between NDT inspections to define the shaft diameters.

Shaft diameter restoration by arc welding.

Different arc welding procedures have been used to repair roll shafts. These procedures have also been designed for a typical 1045 steel shaft. One of the procedures used at Manuelita S.A. sugar mill consists of the use of submerged arc welding (SAW) with neutral flux. The main advantages of SAW are high deposition rates, and the low hydrogen embrittlement sensibility, if the flux is correctly handled.

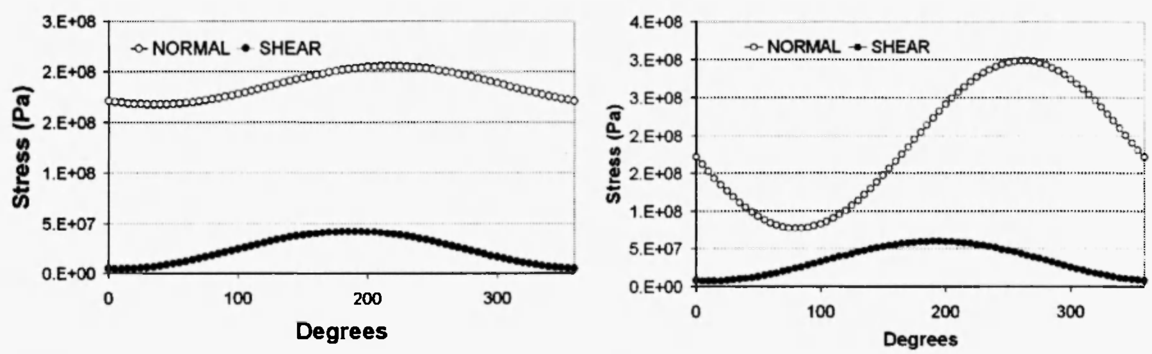
A new stress distribution can be calculated for shaft surface by using a 13 MPa residual stress value for 35.2 kg/mm^2 welding, after 4 hours of heat treatment and superposing its effect to the operational stress, Figure 15. Making use of the equation presented earlier in this paper, using Ki equivalent and equaling it to the Kic of the material, the critical depth of a crack was calculated. The calculated critical crack size was 60 mm for semielliptical and 35 mm for circumferential cracks. Using these crack sizes, a maximum time between NTD inspections of 110 days was required. The minimum detectable crack size considered was 4 mm.

The same repaired shaft without stress relieving was considered. Residual tension welding stresses of 170 MPa for 35.2 kg/mm^2 welds were superimposed on operational stresses for the shaft. Residual stresses acting all around the repaired zone were assumed. The stress distribution can be observed in Figure 16. The calculated critical crack size was 9 mm for semielliptical and 8 mm for circumferential cracks. Using these crack sizes, a time between NDT inspections of 40 days was required. Calculated inspection periods can be extended by 18% if a minimum detectable crack size (depth) of 3 mm is considered instead of 4 mm used in these calculations. The service life can be reduced by an estimated 63% when the stress relief is not applied.



Load state 1 *Load state 5*

Fig. 15: Normal and shear stress distribution in the journal after a stress relieving treatment.



Load state 1 *Load state 5*

Fig. 16: Normal and shear stress distribution without stress relieving.

CONCLUSIONS

- The largest stresses in a top roll shaft are located at the drive-side journal shoulder close to roll shell, thirty-five percent of the cracks found in top roll shafts were detected in this location.
- A direct relationship between lift and radial force was found.
- A plastic zone of 3.35 mm in front of crack was estimated for a studied shaft. The zone must be removed before welding.
- A minimum diameter for a reduced size shaft was calculated. A 5% reduction reduces the required inspection intervals by 38%.

- Reliability of a welded shaft can be impaired if a sound stress relieving process is not used. Service life can be reduced by estimated 63% because residual stresses.
- The shaft diameter reduction can produce an increase of equivalent stresses and stress concentration factors.
- The calculated inspections periods can be extended by 18% if a minimum detectable crack size of 3 mm is considered instead of the 4 mm used in these calculations.

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