**CATEGORY:** SPALLING

**TYPE:** SHELL-CORE BOND FATIGUE SPALLING

**AFFECTS:** DUPLEX ROLLS ONLY (HOT MILLS AND COLD MILLS)

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**CHARACTERISTICS**

Shell-core bond spalling can only occur on duplex rolls and results in catastrophic spalling of the roll barrel. It can be identified as a large area of fracture through the shell layer where fracture flow can be traced back only to the interface between the shell and the core material. This type of fracture is typically symmetrical in appearance with an exposed area of the core material at the centre.

As ribbon fatigue spalling can also exhibit similar features as described above (discussed in Section III.A), it is important to fully inspect the fracture face visually as well as the surrounding area of the barrel using ultrasonic inspection before determining what fracture mechanism occurred. Shell-core bond spalling will show no evidence of surface initiated fatiguing (fatigue ribbon that can be traced back to the surface) either visually on the fracture face or ultrasonically in any areas surrounding the fracture face.

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**EXAMPLES**

*Example 1*
Spalling that has initiated at the shell to core bond of a work roll.
Example 2

Example 2 and 3. Spalling that has initiated at the shell to core bond of a work roll. An area of the core material can be seen at the centre of the fracture. No obvious manufacturing defects are visible. Failure may be aided by elevated rolling stresses especially at the strip edge area.

Example 3
Example 4

Example 4 and 5. Material indications (flux and porosities) visible at the area of the bond. These indications act as stress concentration points and aid crack initiation and subsequent growth.

Example 5
Example 6
Spalling that has initiated at material indications within the bond area, close to the barrel edge (blue arrows)

Example 7
Spalling that has initiated at an area of poor bonding at the barrel edge.
GENERAL MECHANISM

During rolling contact between the back-up roll, work roll and strip results in the formation of sub-surface shear stress. The peak intensity of this shear stress is developed a short distance below the barrel surface. As the roll diameter reduces throughout its service life the shell to core bond moves ever closer to the point of peak stress. If the applied shear stress exceeds the (yield or fatigue) strength of the bond between the shell and the core then a crack will be initiated. Once initiated the crack will propagate outward both circumferentially and longitudinally along the bond zone. Once a critical size and degree of instability has been created within the overlying shell material rapid outward fracture and spalling will occur.

The nature of the manufacturing process employed for duplex rolls means that there will be a level of material indications (such as flux, slag and porosities) present within the bond area of each roll. If the size or quantity of the material indications is abnormally high or the number of applied cycles at a given stress level is excessive, then the material indications can act as stress concentration points and initiate cracks. Likewise abnormal rolling conditions can result in the formation of elevated, localized shear stresses that can also initiate cracks within the bond zone.

PREVENTION

As the mechanisms involved in shell-core bond fatigue spalling are strongly influenced by both manufacturing and service characteristics, the prevention is therefore the responsibility of both the roll manufacturer and the roll user.

Roll Manufacturing

- The roll manufacturer should ensure that the shell-core bond exhibits sufficient strength for the given application.

- The roll manufacturer should ensure that the stress concentration characteristics of the interface between the shell and the core are minimized.

- The roll manufacturer should minimize the presence of material indications within the area of the bond zone. The indications that are present should be small and well distributed.

- Inspection and assessment of the bond as well as the size, quantity and type of indications in each roll should be made and assessed for suitability for the particular rolls application.

- The roll manufacture should ensure sufficient excess shell thickness is provided to ensure the bond zone is not exposed to peak shear stress when close to its designed scrap size.
Roll Usage

- The mill should ensure stable rolling conditions exist and minimize abnormal rolling events or accidents that can result in the formation of excessive sub-surface shear stress.

- It is recommended that in-service ultrasonic inspection of the bond area be carried out on rolls when known rolling incidents have occurred.

- It is recommended that the customer review the mill loading, load distribution, stock removal practice and campaign length to ensure that the shell-core bond is not challenged beyond the capability to resist crack initiation.

- For applications that damage prone, utilize heavy loads, utilize non-uniform loads, or extended roll service life (specifically high speed steel grades) it is recommended that a regular ultrasonic inspection of the bond area be carried out especially in the latter half of a rolls life.

MECHANISM IN DETAIL

Shell-core bond spalling can only occur in duplex rolls. These rolls are manufactured with the working layer of the roll barrel consisting of a hard, wear resistant shell material that is metallurgically bonded (fused) to a core material that makes up the centerline and neck areas.

This fracture mechanism rarely initiates and propagates to spalling within the time of a single campaign.

Shell-core bond fatigue spalling occurs in three distinct stages:

Stage 1 – Crack initiation

During rolling, contact between the back up, work roll and strip results in the formation of sub-surface shear stress that cycles with every revolution of the roll. The peak intensity of this shear stress is developed a short distance below the barrel surface (actual magnitude and depth governed primarily by applied contact pressure), however it will be distributed through the cross section of the shell to the interface between the shell and the core. The magnitude of this cycling shear stress from contact pressure will gradually decrease with radial depth from the peak intensity located a short distance below the surface.

Any stress generated within a material will concentrate at locations of non-homogeneity or non-uniformity. As the interface between the shell and core represents a change from one material to another, it will therefore be an area where applied stress will concentrate (metallurgical “notch”). If the applied contact stress that occurs during rolling results in a concentrated shear stress at the interface that exceeds the strength of the roll material, then a crack can be initiated at this location.
This mechanism of crack initiation at the interface can occur either instantaneously or over time (fatigue).

**Instantaneous Crack Initiation**

If the concentrated shear stress at the interface between the shell and the core exceeds the shear strength of the bond, then a crack will be instantaneously formed. The size of the crack that is formed will depend on the magnitude of the concentrated shear stress. The greater the difference between the concentrated shear stress and the shear strength of the bond, the larger the crack that is instantaneously formed. It is a rare case, but if the magnitude of the concentrated shear stress is extreme, instantaneous crack initiation and propagation to spalling is possible.

**Fatigue Crack Initiation**

Through continuous mill use, the interface between the shell and core material will be subjected to numerous cycles of the applied contact shear stress that is generated below the surface and concentrated at the interface. Even if this concentrated shear stress is less than the shear strength of the bond, spontaneous generation of a small crack can occur once the critical number of cycles has been achieved. This spontaneous generation of cracking at shear stresses less than the shear strength is known as fatigue crack initiation.

The higher the magnitude of the shear stress applied will require a lower number of stress cycles required for a fatigue crack to initiate. Conversely the higher the strength of the bond then the higher the magnitude of applied stress and or fatigue cycles required to initiate a crack.

The magnitude of the concentrated shear stress at the interface will depend not only on operating conditions, but the diameter of the roll as well. As the roll diameter is reduced with each campaign, the interface between the shell and the core is gradually moved closer to the point of peak stress (located below the surface). The bond area is therefore subjected to a steadily increasing concentrated contact shear stress with each campaign which results in a reduction to the number of stress cycle applications before the critical number is reached and a fatigue crack is generated. The initiation of a fatigue crack at the interface between the shell and the core material is therefore most likely to occur during the later stages of a rolls service life (higher shear stress concentration + the interface roll has already been exposed to a large number of stress cycles).

The combination of all of the factors that effect the initiation of a fatigue crack at the interface results in the following common conditions:

- Fatigue crack initiation at the interface is more likely during the later stages of roll life (time is required to achieve the critical number of stress cycles)
- Rolls with long service lives (especially HSS materials) are more likely to exhibit fatigue crack initiation at the interface (longer service life means exposure to more stress cycles)
Rolls in heavily loaded applications are more likely to exhibit fatigue crack initiation at the interface (heavier loading means greater contact shear stress magnitude)

**Stage 2 – Crack propagation over time (fatiguing)**

Once a crack at the interface is present, each revolution in the mill will allow for the crack to propagate a little bit further along the bond area. The propagation of a crack with successive and cycling stress over time is known as fatigue crack propagation.

As the subsurface contact shear stress is oriented primarily in the longitudinal and circumferential directions, the crack propagation is very uniform in all directions away from the initiating crack along the interface only. Due to the unique conditions and material properties at the interface, the typical features normally associated with fatiguing such as arrest marks are typically indistinguishable during this stage.

The rate of crack propagation and growth depends on the magnitude of the concentrated contact shear stress (now represented by the crack as well as the interface as the crack is an extreme non-uniformity) and the size of the separation area. The rate of crack growth will therefore steadily increase under the same operating conditions as the crack grows larger.

**Stage 3 - Spalling**

During fatigue crack propagation at the interface between the shell and the core, the radial driving force for crack propagation is low compared to the longitudinal and circumferential directions until the crack reaches a critical size. The critical size is defined as the point where concentrated contact shear stress at the edges of the crack exceeds the yield strength of the roll material.

At this stage, cracking will begin to propagate in a rapid manner in all directions away from the edges of any part the fatigue ribbon (or in several different locations along the length of a fatigue ribbon) and radially toward the surface until spalling eventually occurs. This rapid crack growth can occur instantaneously or over a short number of cycles (low cycle fatigue).

**Manufacturing and Service Factors**

Duplex rolls are designed to be used from new diameter through the entirety of the expected service life without the onset of cracking at the interface between the shell and the core. The occurrence of cracking and spalling that initiated at shell-core bond will therefore be result of one or more factors. These factors can be related to manufacturing issues, service conditions or a combination of both.

**Manufacturing Factors:**

There are several manufacturing factors that affect the resistance of a roll to the formation of a crack at the interface between the shell and the core as follows:
- **Bond Strength** – The strength of the bond between the shell and the core is determined during manufacturing and is essential to the rolls resistance to the formation of a crack at this location. The stronger the bond, the greater the rolls resistance to crack initiation and propagation.

- **Bond Stress Concentration** – The concentration factor of the interface between the shell and the core is directly related to the radial thickness of the bond. The greater the radial thickness of the bond, the more easily it can distribute the applied stress across the area of the bond and therefore reduce the concentration of stress at this location.

- **Stress Concentration from Material Indications** – Due to inherent attributes of the duplex manufacturing process, it is not unlikely for some material indications to be present at the interface between the shell and the core such as flux, porosity, etc. These indications, like the interface, will act to concentrate stress however, as long as they are small (<5mm or so) and well distributed, they typically do not represent any serious risk of crack initiation. If they are too large and/or are clustered, the stress concentration that can be created at these indications can be large enough in magnitude to exceed the shear strength of the bond or initiate a fatigue crack at a reduced number of stress cycles.

**Service Factors:**

No matter how well a duplex roll is manufactured, the presence of an interface between the shell and the core will always represent a stress concentration site (metallurgical “notch”). This area will therefore always be prone to the loading conditions of the mill which can result in initiation of a crack during abnormal or even normal mill operation. The advancement of mill technology to improve productivity, strip shape and control have likewise challenged the interface to a greater degree than ever before.

- **Abnormal Loading** – Mill incidents can sometimes occur which result in abnormally high contact pressure such as; cobbles, strip breaks, pinches, foreign material, miss-alignment in the mill, mill seizure, etc. All incidents where abnormally high loading occur will result in a sudden increase to the magnitude of the stress that is concentrated at the interface between the shell and the core. Especially for rolls in the later stages of service life (where the interface is closer to the location of peak contact stress intensity), abnormal mill loading can result in a shear stress that initiates a crack at the interface.

- **Non-uniform Loading** – Most mill applications machine the rolls barrels to specific shapes and/or utilize heavy bending, shifting and cross pairing to better control strip shape. These efforts will result in non-uniform loading across the barrel length which will concentrate at specific locations and thereby result in a greater concentration of stress at the interface between the shell and core at those locations. Cracks can be initiated at the interface between the shell and core if the magnitude of concentrated stress is too high.
• Heavy Loading – Application which roll difficult or tough product typically require heavier mill loads. Heavier mill loading will result in an increase to the concentrated contact shear stress at the interface between the shell and core.

• Extended Service Life – Most mills today are looking for ways to extend the service life of the rolls to improve mill productivity such as: extended campaign lengths, less stock removal in-between campaigns, better performing materials (HSS). All such efforts result in an increase to the number of stress cycles that the rolls are exposed to thereby increasing the likelihood of fatigue crack initiation at some stage of the rolls service life.