CATEGORY: SPALLING

TYPE: RIBBON FATIGUE SPALLING
(Also known as: Surface Initiated Spalling, Fatigue Path, Wreck Path, Wagon Tracks, Cat’s Tongue)

AFFECTS: WORK ROLL AND BACK UP ROLL (HOT MILL and COLD MILL)

CHARACTERISTICS

This is the most common classification of spalling for work rolls and back up rolls in all applications. Ribbon fatigue spalling can be identified as one or sometimes multiple areas of spall type fracture on the roll barrel displaying one or more linear ribbon like features created by the propagation of cracks (The ribbon feature is sometime also referred to as: fatigue path, wreck path, wagon track, cat’s tongue, etc). The surface texture and resolution (clarity) of the ribbons can vary greatly depending upon the roll material grade especially in work roll materials (AIC, HiCr and HSS) which can hinder identification, however, the shape and surface texture of the fatigue ribbon does typically exhibit a few characteristic features as follows:

- **Location**
  - Fatigue ribbons and associated spalling can be found at any point on the roll barrel from the very edges to anywhere in between.
  - The fatigue ribbon feature is typically located in the center of the fracture face at the deepest point (radially).
  - The sides of the ribbon path are usually distinct with secondary fracture flow extending longitudinally away from the sides and radially toward the surface.
  - Fracture faces may display a number of fatigue ribbons from one to multiple. Numerous fatigue ribbons in a cluster can sometimes be seen where multiple crack initiation sites were present.
  - Fatigue ribbon can propagate through the shell to the interface between the shell and core. Can be miss-diagnosed as shell-core interface separation spalling.

- **Shape**
  - Fatigue ribbons can widely vary in size and width from one incident to another, but primarily appears as a circumferentially oriented “path” propagating through and into the shell material (ie getting radially deeper).
    - Typically gets wider with depth away from the surface where it initiated until an “equilibrium” width is reached
    - Width can vary from very small (<5mm wide) to very wide (>150mm)
    - Length of the ribbon path on the fracture face depends on how much has been exposed and total propagation length.
Propagation length can be short (<50mm) up to several revolutions around the roll circumference
  - Fatigue ribbons can appear to propagate in a straight circumferentially oriented path or can “meander” toward one side of the barrel length (or even back and forth).

- Fatigue Ribbon Surface Texture
  - May appear discolored (stained) or burnished (shiny/rubbed) relative to the surrounding fracture face
  - Should exhibit fatigue arrest marks (also known as “beach” marks), but may be difficult to distinguish especially in work roll materials (AIC, HiCr Iron and HSS).
    - Arrest marks appear as regular, repeating, semi-circular “arcs” or “horseshoes” located within the fatigue ribbon
    - The center of each arrest mark is always pointed in the direction of crack propagation (almost like an arced arrow head pointed in its direction of travel).

**EXAMPLE**

![Example 1](image_url)

**Example 1**
Discolored fatigue ribbon on the spall fracture surface of a back up roll. Arrows indicate direction of propagation
Example 2

Fatigue ribbon visible on the spall fracture surface of a work roll. Semi circular fan shaped arrest or “beach marks” can clearly be seen (arrows). These arrest marks indicate the direction for propagation of the ribbon in this case from top to bottom of the image.
Example 2
Discolored fatigue ribbon at the centre of a back up roll barrel spall. Arrows highlight the direction of propagation

Example 3
Discolored fatigue ribbon within the barrel spall of a work roll.
Fatigue ribbons visible on the spall surface of work rolls (example 4 and 5). The full extent of the crack ribbons has not been exposed by the spalling in each case. Ultrasonic examination has been able to trace an initiation point.
Less distinct fatigue ribbons visible on the spall surfaces of a work rolls (examples 6 and 7). Direction of propagation indicated by arrows.
Example 8

Fatigue ribbons visible within spalling at the edges of back up rolls. Arrows indicate the direction of propagation.

Example 9

Barrel edge spall with fatigue ribbon. Arrows highlight direction of propagation.
Example 10
Multiple, extensive fatigue ribbons (blue arrows) and initiation points (yellow arrows) visible on the spall surface of a work roll.

Example 11
Multiple discolored crack ribbons on the spall surface of a work roll. In this instance the centre crack has reversed direction (blue arrow), as crack has been present when roll has been used in top and then bottom positions of the mill. Crack ribbon was not detected or removed during intermediary re-grinding operation.
Fatigue ribbon visible on the spall surface (blue arrow) and its initiation point (yellow arrow).

Two fatigue ribbons adjacent to one another on a spall surface.
Example 15

Cross section through a crack ribbon within the shell layer of a duplex work roll. Arrow indicates the location of a crack visible at the roll surface.

Example 12

Crack ribbon upon the fracture surface of a spalled out piece of back up roll
GENERAL MECHANISM

If a crack is present at the surface of a work roll it will be propagated in a fatigue mode when exposed to an applied stress of sufficient magnitude. The rolling process itself results in the formation of a significant sub-surface shear stress (Hertz stress) with a peak intensity located a short distance below the barrel surface. Any crack of sufficient depth will act as a concentration point for this stress. Propagation of the crack tip will occur in the reverse direction to the rolling direction at the application of each (shear) stress cycle. The propagation of the crack at each cycle will result in the formation of a semi circular arrest or “beach mark”. Propagation of the crack and the formation of the ribbon will occur initially tangential to the surface until such a point that the crack intersects the shell to core bond zone (duplex rolls) or the base or the hardened layer (mono block rolls). At this point the orientation of the ribbon and direction of propagation will progress parallel to the roll surface. Discoloration of the crack ribbon occurs due to the ingress of mill fluids (water, oils etc) through the open initiation crack at the roll surface. Once the crack ribbon has reached a critical extent the instability that is generated in the material overlying the ribbon allows for rapid, instantaneous outward fracture and spalling off of the surface material.

PREVENTION

Fatigue ribbon spalling is usually catastrophic, meaning that the depth of the fracture typically renders the roll un-repairable. Safety must also be considered as this type of spalling can sometimes also occur in a violent manner.

- It is essential that all cracks or defects be removed from the surface of the roll prior to mill service. For early stand hot strip mill work rolls and roughing mill work rolls, the guidelines given in sections II.A, II.E, II.F, II.G, and II.K regarding safe crack management should be followed. For all other applications (cold mill work rolls and all back-up rolls), all cracks should be completely removed.

- When accidents or abnormalities in the rolling process occur it is essential that rolls be inspected as soon as practicable and any necessary rectifications made to remove any defects present.

- Consistent use of eddy current and ultrasonic inspection techniques on every roll after completion of the grinding operation is highly recommended to ensure that the roll is free from surface damage that may initiate a fatigue ribbon. Secondary inspection procedures and techniques such magnetic particle and dye penetrant inspection should be employed as well in all areas where known damage occurred. Visual inspection alone is not recommended.

- Ensure sufficient stock removal after every campaign to insure that any surface damage induced during the last campaign is eliminated.

- Review the roll specifications with the manufacturer to ensure that the roll supplied will be the best balance between wear resistance and damage resistance for a given application.
MECHANISM IN DETAIL

Ribbon fatigue spalling is the most common mechanism for spalling of work rolls and back-up rolls in all applications. In almost every case, it is the result of mill induced damage (cracks) located at or near the surface of the roll barrel during mill operation. Although this fracture mechanism can occur within the same campaign where the mill induced cracking was generated, it is usually detectable in-between campaigns using standard inspection methods where the damage can still be removed before catastrophic spalling occurs. Fatigue ribbon spalling occurs in several distinct stages (Figure 1):

![FIGURE 1](image)

**STAGE 1 – Crack Initiation**

A crack is initiated at or near the roll surface. For a mill induced crack to advance to Stage 2 and beyond, it typically has to be oriented in the longitudinal direction and be of sufficient size and depth to be affected by the particular mill application. In general, hot mill work roll applications can typically tolerate a larger and deeper crack than cold mill work roll applications without them advancing to Stage 2, however the guidelines for crack maintenance as specified in each of the Sections II.E, II.F, II.G, and II.K should be strictly adhered to in order to prevent crack growth. Back-up rolls in all applications exhibit similar behavior with regard to crack growth potential and should therefore be handled equally.
As was already stated, the majority of fatigue ribbon spalling incidents initiate at mill induced damage. For work rolls, this is most likely at either thermally manifested firecracks or mechanically manifested cracks from localized contact overload (see Sections II.A, II.E, II.F, II.G, and II.K for some of the most common causes of mill induced cracking on work rolls). For back-up rolls, cracks that have the potential to develop into fatigue ribbons are more often the result of subsurface contact stress cracking (see Section III.C – Contact Stress Spalling) or mechanical contact overload surface cracking (see Section II.K – Mechanical Marking, Cracking and Spalling).

**STAGE 2 – Crack Propagation Over Time Through the Shell or Hardened Layer (Fatigue)**

With each revolution in the mill, every point on the roll barrel surface is exposed to radial stress from contact pressure as well as tangential stress from friction when passing through the roll bite or contact zone between the work roll and back-up roll. These stresses will concentrate at any non-uniformity within the affected area including cracks. The magnitude of stress concentration of each crack will depend on several factors including crack size (length, depth, width), angle, orientation (longitudinally oriented cracks resulting in highest concentration), location, etc. If a crack is present at the roll surface of sufficient stress concentration characteristics, the cycling of combined contact pressure and frictional stress will result in some radial and circumferential propagation of the crack into the rolls interior with each revolution. The propagation of a crack with successive application of stress over time is known as fatigue propagation.

Once fatigue crack propagation has begun, each revolution in the mill will allow for the crack to propagate a little bit further forming the fatigue ribbon feature described in the Characteristics section above. The progress of the crack propagation can be highlighted by presence of fatigue arrest marks where each arrest mark denotes the location where crack propagation ended on a particular cycle before the next application of stress (see Characteristics section above). The direction of crack propagation depends on the magnitude of the stresses which are applied to the crack as follows:

- **Friction** – Friction within the roll bite and roll-to-roll contact zone will result in a stress that is parallel to the tangent of the roll surface and oriented opposite the direction of roll rotation. This stress will force the crack to propagate in the circumferentially in the opposite direction of roll rotation.

- **Contact Pressure + Residual Manufacturing Stress** – Contact pressure within the roll bite or roll contact zone combined with the residual stress that is always present with the hard, wear resistant part of the roll barrel will result in a stress that is oriented in the radial direction. This stress will force the crack to propagate in the radial direction deeper into the rolls interior.
In general, cracks located at or near the surface will always propagate both radially and circumferentially into the rolls interior due to the combination of the forces described above. How fast a crack propagates in either of the radial or circumferential directions will depend on the balance of forces in a given application as well as the magnitude of residual manufacturing stress. Some fatigue ribbons will propagate more circumferentially than radially resulting in a long fatigue ribbon that slowly progresses deeper into the rolls interior, others propagate more radially at first, plunging deep into the rolls cross section quickly before beginning to propagate in a more circumferential manner.

If the crack at the surface is wide enough (open), then mill fluids may be drawn into the open crack and down into the fatigue ribbon during rolling. The presence of the mill fluids (water, oils, coolant, etc) will discolor the surface of the fatigue ribbon which may highlight against a fresh fracture face when spalling occurs.

The fatigue ribbon will continue to propagate radially and circumferentially through the depth of the shell until it reaches the interface between the shell and the core material.

**STAGE 3 – Continued Crack Propagation at The Interface or Neutral Zone (Fatigue)**

With continued rolling, the fatigue ribbon will continue to propagate radially and circumferentially through the depth of the shell until it reaches the interface between the shell and the core material (duplex work rolls) or the base of the hardened layer (monoblock rolls). At this location, the radial driving force for crack propagation is significantly reduced compared to the material properties which prevent the crack from propagating any deeper into the rolls cross section. With continued rolling, the fatigue ribbon will therefore continue to propagate circumferentially around the roll at the interface between the shell and the core.

For work rolls (duplex), the typical features associated with fatigue ribbons, however begin to become a bit indistinguishable at the interface between the shell and the core. The material properties of this location will generally mask any of typical textures of fatigue ribbon that are found in the shell material such as arrest marks. This stage of fatigue is therefore quite often mis-diagnosed as shell-core bond separation spalling if only this stage is exposed when spalling occurs (see Section III.B – Shell-Core Bond Separation). In this case, ultrasonic inspection should be able to expose the reminder of the fatigue ribbon that is still hidden beneath the surface and trace it back towards the surface where it initiated.
STAGE 4 – Spalling

Spalling can actually occur at any point during Stages 2 and 3 depending on the rate of fatigue ribbon growth, the magnitude of the induced stresses and the strength of the roll material.

During rolling, the same stresses that are driving the crack to propagate forward radially and circumferentially are also concentrated around all edges of the fatigue ribbon. The fatigue ribbon will therefore continue to propagate until it reaches a critical size where the concentration of the applied rolling stresses on the edges 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).

Final Discussion Points

It is the unique balance and combination of friction, contact pressure and residual manufacturing stress present near the roll surface that results in the formation of a fatigue ribbon. It is for this reason that the presence and identification of a fatigue ribbon contained in the subsurface of a roll or on the fracture face of a spall will always indicate that it initiated at or just below the roll surface (within a few millimeters of the roll surface where friction forces are still high in magnitude).

As was stated above, the progress of the cracks propagation can be highlighted by presence of fatigue arrest marks. It should be noted however that each arrest mark may not represent each rotation in the mill, but more likely the change from one stress cycle state to another (i.e. they could represent the progress from one bar to another, one coil to another, one campaign to another, etc). Fatigue arrest marks can therefore not be a reliable way to determine the total amount of time that a fatigue ribbon path had been developing before spalling occurred.

Also as stated above, this mechanism can sometime be miss-diagnosed as shell-core bond separation (see Section III.B Shell-Core Bond Related Spalling) as it is possible for the fatigue ribbon to propagate through the shell to the interface between the shell and core. When spalling occurs, the portion of the fatigue ribbon that propagated though the shell may be hidden exposing only the portion of the fracture propagating through the interface zone. This condition can sometimes look similar to the characteristics described in section III.B Shell-Core Bond Separation). Ultrasonic inspection should therefore always be performed after a spalling incident to fully “expose” the entire fracture face. Fatigue ribbons will therefore be able to highlighted and traced back to their initiation site at or near the surface.