This is the most common classification of spalling for static cast monoblock rolls (back-up rolls in particular) in all applications. It can also occur on duplex work rolls, but is less common and is usually to a lesser degree.

Contact stress fracture can be identified as an area exhibiting relatively shallow barrel surface cracking and spalling (typically <25mm in depth). As this cracking and spalling mechanism initiates just below the rolling surface, affected areas of the surface may only initially exhibit surface indentation and associated cracking if spalling has not yet occurred. This will be similar appearance to mechanical marking, cracking and spalling (see Section II.K) which is a similar mechanism.

When exposed, the fracture faces are usually shiny or “rubbed” (unless oxidation has occurred) and are typically described as being, multi-faceted, saw toothed, “crumbly”, cratered or even “ice cream scooped” in appearance. Close examination will reveal that fracture appears to initiate at multiple areas all over the fracture face. Fracture can be seen to flow in almost every direction from multiple points below the surface toward the surface resulting in the typical cratered or “crumbly” appearance.

The affected area can vary in size from small individual spalls to very large areas of the roll barrel. The fracturing can be contained in localized areas or be present in bands extending around the full roll circumference.

Ribbon fatigue spalling can also initiate at areas of contact stress cracking and spalling (see section III.A) which will result in a larger and deeper spall. In these cases, when the fatigue ribbon is traced back to the initiation site, it will be found to initiate just below the surface at an area exhibiting the characteristics of contact stress spalling.
Example 1
Contact stress spalling at the barrel edge of a back up roll.

Example 2
Close up of an area of contact stress spalling at the barrel edge of a back up roll. The multi-faceted or crumbly appearance of the fracture is clearly evident. Ultrasonic examination of this roll showed this cracking to be present around the full barrel circumference not yet developed to full spalling.
Example 3
A small localized area of contact stress spalling present at the surface of a back up roll.

Example 4
A localized area of contact stress spalling and indentations at the barrel surface of a back up roll.
Example 5
An area of a back up roll barrel surface with numerous indentations. Within the indentations are numerous cracks. This will have ultimately developed into contact stress spalling.
Example 6
Contact stress spalling at the edge of a back up roll barrel. A crack ribbon can be seen at the centre of the spalled area.
Example 7
High Cycle contact stress spalling at the barrel edge of a back up roll.

Example 8
Contact stress spall after plunge grinding. The magnitude of the sub-surface cracking can clearly be seen.
As a result of the mill loads applied to the roll stack during rolling a localized flattening of the roll barrel surface occurs at the point of contact between the work roll and the back-up roll. This flattening results in the formation a shear stress (commonly referred to as Hertz Stress) with peak intensity at a given distance below the point of contact (see figure 1 and 2). If the shear stress developed exceeds the strength of the roll material at that location cracks will be initiated. Once formed these cracks will propagate outward toward the barrel surface at which point spalling occurs. In some instances it is also possible for these cracks to propagate inward and initiate a ribbon fatigue spall.
Contact stress spalling can occur via two modes:

- **Instantaneous Mode.**

A sudden increase in Hertz shear stress above that of the strength of the roll material can be created when a point overload is applied to the barrel surface. Mill accidents such as cobbles, skids, strip wraps and welds and when debris passes between the roll gaps can all result in instantaneous point overloading. Cracks once formed will then propagate outward in a fatigue mode and ultimately result in surface spalling. In extreme cases crack initiation and spalling can occur instantaneously.
High Cycle Mode.

In this mode cracks are formed without instantaneous point overloads and initiate over a specific period of time dependant on the number of cycles and the stress applied. Repeated applications of stress, even though below the strength of the roll material, can initiated cracks once the fatigue limit of the material is reached.

When rolls are ground and loaded into the mill the stress distribution at the point of contact between the back-up roll and work roll is uniform. However as the campaign progresses the barrel profiles of both rolls change as a result of wear at the barrel centre positions. This change in profile results in an increase in contact stress at the barrel edges outside of the rolling contact width. Additional factors such as work roll bending and inadequate edge relief can also aid in an increase in edge stress. This localized increase in stress throughout the length of a rolling campaign can then be sufficient to breach the roll materials fatigue limit and imitate cracks below the surface at the point of peak shear stress. Once formed the cracks will propagate outward and ultimately result in spalling.

High cycle contact stress spalling predominantly affects back up rolls due to the longer campaign lengths (total number of cycles) encountered.

PREVENTION

- Minimize the occurrence of rolling accidents likely to induce localized point overloading.
- Ensure adequate edge relief/chamfering is applied to back up rolls to alleviate localized contact stress.
- Review roll shape profile (crown, CVC shape, etc) to ensure that the contact pressure stress distribution does not result in a contact shear stress which results in the initiation of contact stress cracking.
- Review the material specification, hardness specification and hardenability specification with the roll supplier to ensure that the shear strength of the roll material is adequate to resist the onset of contact stress cracking in the given application (normal operating conditions).
- Review the campaign length to ensure that the rolls achieve optimum performance, but are not exposed to the critical number of cycles before an opportunity to grind. The campaign length will need to be balanced with the grinding practice to ensure optimum performance, but with adequate stock removal to ensure that contact stress cracking/spalling do not occur.
- Review the grinding practice to ensure adequate stock removals during grinding to achieve the following:
  - Complete removal of all subsurface contact stress cracks that formed during a previous campaign.
Ensure that the roll consumption rate enables the material to provide the optimum performance, but also consumes the subsurface material exposed to fatigue damage before the initiation of fatigue cracking (see mechanism above for more detail).

The following procedure is recommended:

- Grind the barrel to remove the mill induced wear contour and any visible damage (indentations, cracks, etc).

- Inspect the roll barrel to ensure that all damage has been removed. Some mills use automated eddy current and ultrasonic inspection systems during the grinding operation to ensure that the roll is free from residual surface and subsurface mill damage.

- Test the hardness across the length of the roll barrel
  - If the average hardness exceeds 3 HSc (15 HLe) points above the predicted hardness, then grind more stock off of the barrel and retest
  - If the average hardness is within 3 HSc (15 HLe) points of the predicted hardness, then the roll is acceptable for mill service

The purpose for grinding the roll until the surface hardness is less than 3 HSc above the predicted hardness is to ensure that the majority of work hardening that was induced during mill service is removed.

- Ensure that all repairs to back-up rolls result in complete removal of all cracking and spalling. All repairs should be performed using the criteria given above in the Repair Procedure section.

- Investigate inspection practices using automated ultrasonic inspection for the near surface.
MECHANISM IN DETAIL

Contact stress spalling is the most common mechanism for spalling of back-up rolls in all applications. In almost every case, it is the result of mill induced damage (cracks) that are formed just below the surface of the roll barrel during mill operation. As this is a sub-surface initiating crack mechanism, it is not easily detectable in-between mill campaigns. It can be located using straight beam ultrasonic inspection using a transducer with a delay block to allow for clear resolution just below the surface. Some of the automated inspection packages available today do include this type of inspection, otherwise manual ultrasonic inspection using a straight beam transducer is required.

Contact stress spalling occurs in three distinct stages.

**Stage 1 – Crack Initiation**

During rolling, the applied mill loads concentrated at the contact point between the back-up roll, work roll and the strip results in the formation of subsurface shear stress that cycles with every revolution of the roll (commonly referred to as Hertzian Stress). As can be seen in Figures 1 and 2 which shows the stress distribution at the contact point, the maximum resultant shear stress is actually located a short distance below the surface of the roll. The magnitude of the maximum resultant shear stress and its location show are directly dependant on the magnitude of the applied load and the diameters of the rolls in contact. As the magnitude of the applied load increases (contact pressure), the magnitude of the maximum resultant shear stress increases as well as the radial depth at which the maximum resultant shear stress is located. This means that the greater the contact pressure, the greater the depth and intensity of maximum resultant shear stress. If the maximum resultant shear stress generated during rolling (or other contact) exceeds the shear strength of the roll material, then cracks can be initiated instantaneously at the subsurface location of maximum resultant shear stress. Alternatively, even if the resultant shear stress is below the shear strength of the roll material if the stress is above the fatigue limit then cracks will still initiate during extended use.
Schematic diagrams of the stress profile between two rolls in contact under load. Red arrow highlights the generic radial shear stress profile generated within the barrel. Blue arrow highlights the location of maximum shear stress (Hertzian Stress).
This mechanism of crack initiation at the subsurface location of maximum resultant shear stress can occur either instantaneously or over time (fatigue).

**Instantaneous Crack Initiation**

If the maximum resultant shear stress exceeds the shear strength of the roll material, then multiple cracks will be instantaneously formed at the subsurface location of maximum resultant shear stress. At this depth, the orientation of the shear stress from contact is primarily oriented parallel to the roll surface tangent. The numerous subsurface cracks that are formed are therefore also oriented parallel to the roll surface tangent and will be dispersed over the entire area affected area. As was shown above, the size and depth of the cracks that are formed will be directly dependant on the contact load.

Instantaneous contact stress crack formation is typically the result of a mill event which results in abnormal and/or non-uniform contact loading. Some of the typical mill events which can result in instantaneous crack initiation are: strip breaks, cobbles, spalling of one of the rolls in the mill train, debris and/or strip passing between the roll-to-roll contact zone, improper handling of the rolls, etc. Due to the severe nature of abnormal contact stress events, the surface of the roll can, but not always, show signs of damage such as discoloration and/or mechanical indentation. In very severe cases, the instantaneous manifestation of subsurface contact stress cracks and propagation of the cracks to spalling can occur during the same loading event.

Contact stress cracking and/or associated spalling can usually be identified as being the result of an instantaneous contact stress overload by the following characteristics:

- Cracks/spalling only found in a localized area on the roll barrel (ie not found around the entire circumference)

- Cracks/spalling can found associated with indications of mill induced damage such as discoloration and/or indentation of the roll surface prior to grinding (grinding will typically remove all evidence of associated mill damage).

- A known mill event occurred during the rolls previous or last few campaigns.

- Maximum radial depth of the cracks/spalling found to be deeper than what would be calculated for normal loading (using the formula given above in Figures 1 and 2). The calculations shown in Figures 1 and 2 can be used to calculate the expected magnitude and depth maximum resultant shear stress ($P_{\text{max}} = \text{magnitude of maximum resultant shear stress}, 0.39b = \text{radial depth}$). If the cracks/spalls are found to be significantly deeper than what is calculated using normal loading conditions, then the cracks/spalls are most likely the result of abnormal mill damage.
Fatigue Crack Initiation

Through continuous mill use, the roll is subject to numerous cycles of the contact shear stress that is generated below the surface of the roll barrel. Even if the contact stress is less than the shear strength of the roll material, spontaneous generation of small cracks can occur over time once the critical number of stress cycles has been achieved. This spontaneous generation of cracks at shear stress less than the shear strength is known as fatigue crack initiation. Back-up rolls are particularly sensitive to contact stress fatigue crack initiation due to the significantly longer campaign lengths than are typical for work rolls which results in a greater number of total stress cycles that back-up rolls are exposed to.

Shear stress from contact pressure is primarily oriented parallel to the roll surface tangent. The numerous subsurface cracks that are formed are therefore also oriented parallel to the roll surface tangent and will be dispersed over the entire area affected area. As was shown above, the size and depth of the cracks that are formed will be directly dependant on the contact load.

The number of cycles required for a fatigue crack to initiate depends on the magnitude of the contact shear stress and the shear strength of the roll material. The greater the difference between the contact shear stress and the shear strength of the roll material, the greater number of cycles required to initiate a fatigue crack.

Contact stress fatigue crack initiation can occur as the result of normal rolling conditions and can be expected if the rolls campaign length and maintenance practice is not balanced to ensure good performance and adequate removal or “relocation” of fatigue damage. During the course of a single campaign, the subsurface location of maximum resultant shear stress is the most likely location where fatigue cracking could begin to initiate. As the roll is ground in-between campaigns, the subsurface location of maximum resultant shear stress will be “relocated” closer to the surface where it will be subjected to a cycling shear stress of reduced magnitude. Even though a reduction to the applied cycling contact shear stress will require an increased number of stress cycles to initiate fatigue crack, fatigue damage that was done during a previous campaign and/or campaigns is additive which could still be subject to fatigue crack initiation even at a reduced applied contact shear stress. It is for this reason that the campaign lengths and grinding practices should ensure that the following conditions are met:

- The campaign length should ensure that the roll is not subjected to the critical number to stress cycles to initiate fatigue cracks at the location of maximum resultant shear stress during the course of a single campaign
- The grinding practice should include adequate stock removal to ensure that areas previously subjected to the maximum resultant shear stress are “relocated” further away at a rate so that the critical number of cycles for initiation of contact stress fatigue cracks is not achieved.
As most rolls barrels are ground to a profile (shape) for strip control, the distribution of contact stress is not uniform across the entire barrel length. Areas of the barrel which are exposed to elevated or concentrated areas of contact stress are therefore more likely to exhibit initiation of subsurface contact stress fatigue cracks. Some of the most common areas for contact stress concentration are: strip edges, barrel edges, high points of shape profile (barrel center on crowned rolls, high point on CVC shaped rolls, etc.). Once contact stress fatigue cracking begins, it would be expected to be found around the entire circumference (assuming a consistent mill load for every full revolution).

Contact stress spalling can therefore usually be identified as being the result of fatigue initiation by the following characteristics:

- Cracks/spalling found around the entire circumference. Usually associated with a location of the roll barrel where stress is concentrated (likely locations include: barrel edge, strip edge, barrel center (crowned rolls), or any other high point on a profile.
- Typically no indication of mill damage noted anywhere on the barrel prior to grinding.
- No mill events reported during the last few campaigns where abnormal loads would have occurred
- Maximum radial depth of the cracks/spalling found to be within what would be calculated for normal loading (using the formula given above in Figures 1 and 2). The calculations shown in Figures 1 and 2 can be used to calculate the expected magnitude and depth maximum resultant shear stress ($P_{\text{max}}$ = magnitude of maximum resultant shear stress, $0.39b$ = radial depth). If the cracks/spalls are found to be close to the depth that is calculated using normal loading conditions, then the cracks/spalls are most likely the result of abnormal mill damage

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

Once cracks below the surface of the roll barrel are present (including instantaneous cracks), each revolution in the mill will allow for the crack to propagate a little bit further away from the initial size created in Step 1. The combination of contact shear stress, residual stress any tangential stress from friction determines the direction of propagation.

For most applications (especially true for back-up roll applications), the driving force for crack propagation is greater in the radial direction toward the surface, than in any other direction. This means that with each revolution in the mill, the cracks will propagate a little bit in all longitudinal and circumferential directions, but mainly toward the surface of the roll barrel. Due to the number of cracks initially present as well as the unique conditions present, the typical features normally associated with fatiguing such as arrest marks are visually indistinguishable during this stage.
The rate of crack propagation and growth depends on the magnitude of the contact shear stress, initial size and number of the cracks in the affected area.

For some applications (especially true for work roll applications), the driving force for crack propagation is greater in the tangential (from friction) and radial direction into the rolls interior (combination of residual manufacturing stress and applied contact stress). In these cases, the cracks will begin to propagate radially and circumferential direction into the rolls interior in the form of fatigue ribbon (see Section III.A – Ribbon Fatigue). For the most part, ribbon fatigue that initiates from subsurface contact stress cracking will continue to propagate to a larger, more catastrophic spall. If the entire fracture face is exposed including the contact stress cracking, then the fatigue ribbon will be able to be visually traced back to the area which exhibits the typical features of contact stress cracking/spall. If the subsurface contact stress cracking is not exposed, then fatigue ribbon can be traced visually (or ultrasonically) back toward the surface, but no crack will be able to be found directly on the surface of the roll.

**Stage 3 – Spalling**

With continued mill service and application of stress cycles, the cracks will continue to propagate toward the surface until spalling occurs. As each contact stress crack varies in initial size, the propagation rate will differ between each crack. When spalling does eventually occur, it will begin at the most severe areas first, leaving the remaining cracks still unexposed until further application of stress propagates them further.

**Repair Procedure (Back-up rolls only)**

Depending on the severity of the contact stress cracking and/or spalling that occurs, back-up rolls are often repairable.

To prevent further propagation of existing cracking to spalling, it is recommended that all existing subsurface damage be fully removed before the rolls next campaign. It is therefore important to perform the following minimum inspection techniques when a roll begins to exhibit contact stress spalling to fully assess the total extent of the damage:

- Ultrasonic inspection using a dual probe, straight beam transducer of the entire area surrounding the spalling that is visually evident. This is required as not all of the contact stress cracking may have propagated to the surface yet.

- Visual and ultrasonic inspection of the entire circumference to ensure that no other areas of contact stress cracking are present.

If unexposed subsurface cracking is found around the entire circumference, then the entire roll barrel will have to be machined with enough stock removal to ensure complete removal of all existing cracks.
If the affected area(s) are found to be localized, then the area can be locally and manually ground using a “dish” procedure to ensure complete removal of all cracks and spall damage.