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FAILURE INVESTIGATION OF HIGH-CHROMIUM CAST IRON ROLLS

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ABSTRACT

An investigation was made to look into the factors causing premature failures in high-chromium cast iron rolls. It has been verified that firecracking which results from thermal fatigue serves as failure initiation sites and thus greatly limits the service life of rolls.

Thermal fatigue mechanism is described and how it progresses to barrel breakage and spalling.

I. INTRODUCTION

Rolling steel at elevated temperatures referred to as rolling is one of the most important industrial processes for a greater volume of material is worked by rolling than by any other technique.<1> Key tools in the rolling process are the rolls themselves.

In general, rolls contribute about 5-15% of overall production costs.<2> They are the single greatest expense of operating a rolling mill. This expense is escalated by unscheduled downtime due to premature roll failures and wear related problems which necessitate work roll changes.

As rolls have to be changed frequently, a large stock of rolls must be maintained as inventory. In addition, expensive machines often housed in valuable space must be provided to dress a roll before the roll can be replaced in the mill. In many cases, roll life is actually only 40% "service use" while the remaining 60% is for "repair or damage". <3>

This paper aims to look into the factors causing premature failures in high-chromium cast iron rolls in a hot rolling mill over a six-month period and possible remedial measures to minimize their occurrence.

1.1 Work Roll Properties

The work rolls have to witstand severe extremes of temperature and load. Figure 1 summarizes the differences in the work roll properties which are required in a typical hot strip mill. <4> The temperature profile of the hot strip decreases from the roughing stage to the last

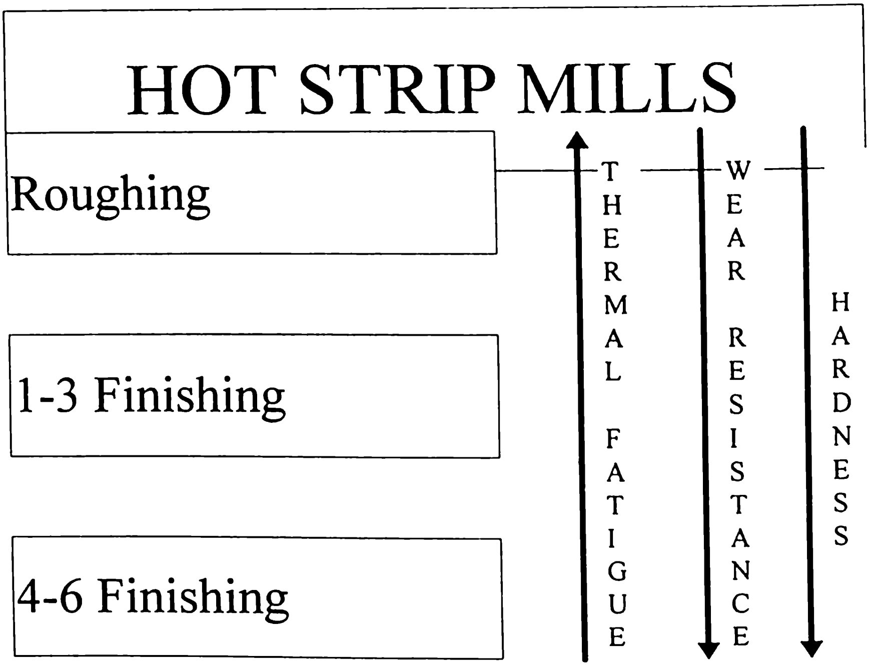


Figure 1. Hot Strip Mills

stand with corresponding increase in velocity as it reduces in thickness. At the initial stage of the rolling process (Roughing and 1-3 Finishing), thermal fatigue resistance is the most important property since it is required with increased general strength of the roll material to withstand the high rolling loads due to high reductions. In this stage, the high chrome family of materials are favored over other work roll materials in view of its higher compressive yield strength at elevated temperatures. <4> This can be seen in Figure 2. As such, it therefore has much better thermal fatigue characteristics. At the finishing end, due to higher abrasive wear, the wear resistance has to increase with a corresponding increase in hardness.

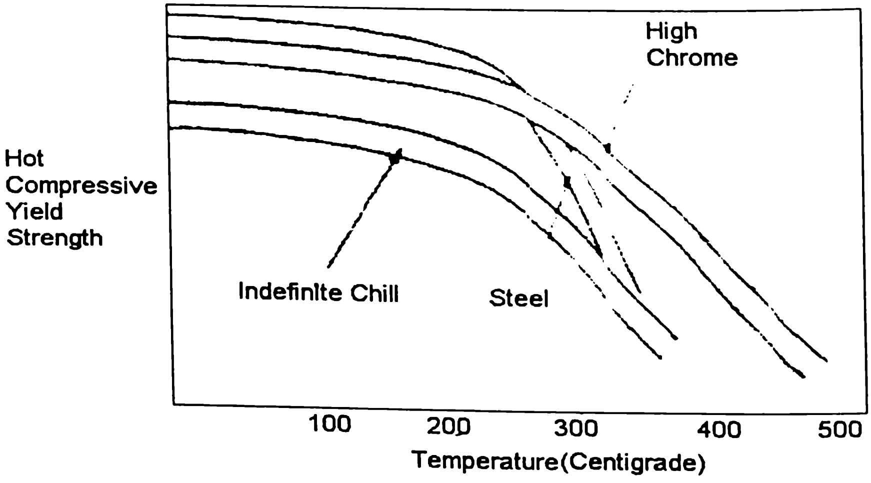


Figure 2. Hot Compressive Yield Strength

1.2 Mechanisms Leading to Roll Surface Deterioration

There are many possible mechanisms which lead to roll surface deterioration in hot strip mills. These are as follows:<5>

a. abrasion due to hard iron oxides formed on surface of rolled material
b. thermal fatigue
c. fatigue due to the roll separating force
d. fatigue due to force between work roll and back-up roll (which may be increased by the wear patterns of the work roll)
e. scale pick-up
f. stress corrosion
g. abrasion due to slip between roll surfaces and plastically-deformed strip
h. electrochemical corrosion
I. hydrostatic forces

The first two, abrasion due to hard iron oxides and thermal fatigue are believed to be the major factors. Thermal fatigue can cause surface deterioration due to a fine fire crazing pattern.

1.3 Thermal Fatigue

Figure 3 illustrates the generation of thermal stresses during rolling. Any one point on the roll surface is alternately heated by contact with the strip and cooled by water jets. In the roll bite region, the surface of the work rolls are in contact with steel strip at a temperature of about 1,150 °C compared to the mean or bulk temperature of the roll which is maintained at about 50-150 °C. <5> Heat will flow from the strip to the roll over the area of contact between roll and

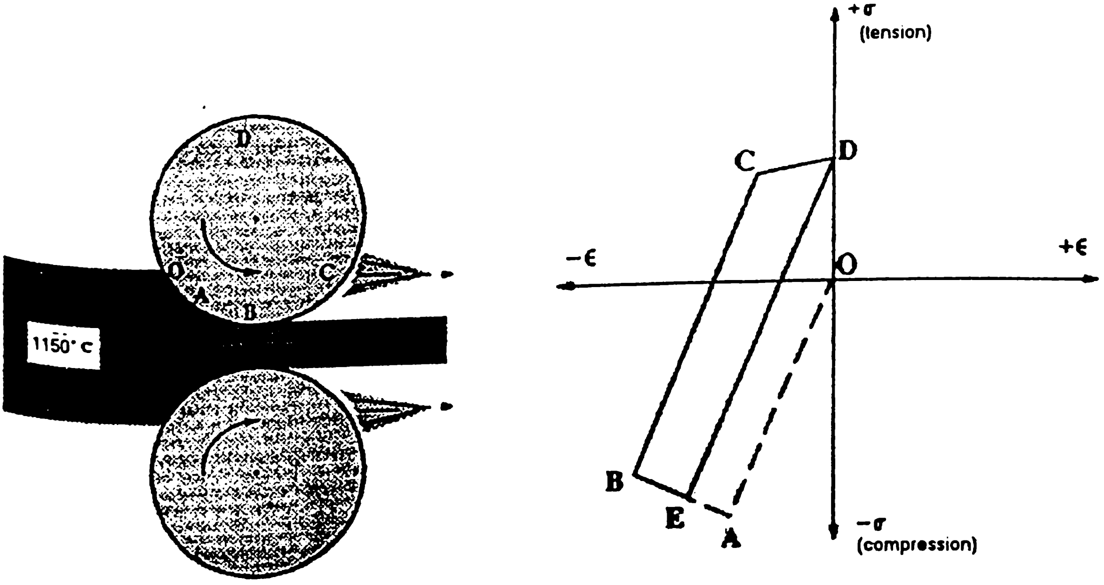


Figure 3. Thermal Fatigue

strip. Referring again to Figure 3, several areas have been marked around the circumference of the roll and on the hysteresis diagram, the stress-strain levels of a small element at each area of the surface are shown.

Consider an element of the roll surface at point O which comes into contact with the steel strip on the first working revolution of the roll. As the temperature of the element increases, it attempts to expand. However, this expansion is prevented by the interior of the roll which has not undergone this rapid heating and therefore constrains this small surface element. This results in the development of a compressive stress in the roll surface in the circumferential direction. Depending on the temperature difference between the surface and the interior of the roll, this compressive stress can be severe enough to cause yielding of the roll surface material. When the compressive strength of the roll material is lower than this compressive stress, plastic deformation occurs in the roll surface area. <6>

The circumferential compressive stress increases as the surface temperature rises. Initially, the roll surface material deforms elastically along OA. As the surface temperature continues to rise, the compressive yield stress of the roll material is reached and the surface begins to deform plastically at point A. With further increases in temperature at AB, an increase in compressive strain is accompanied by a reduction in compressive stress.

As the element comes out of the roll bite, it is cooled by the water cooling systems. The element is then put under a reverse stress system and moves into the elastic tensile stress system between B and C. It is inevitable that the element will be cooled below the average roll temperature by the cooling water and cause tensile plastic deformation in the region C to D. Once the surface element has cooled to the same temperature as the bulk roll temperature, only residual tensile stress remains at zero strain.

On the next revolution, the surface is heated by the strip again and deforms elastically along DE and then follows the part of cycle EB. On cooling, the surface deformation follows the previous cycle BC, CD. Thus, a hysteresis loop is set up, around which the roll surface matcrial deforms on the subsequent revolutions of the roll. On each revolution, the surface undergoes plastic strain in compression and in tension. The result is thermal fatigue which generally results in the fine networking of cracks in the roll surface known as "firecracking". The area covered by the hysteresis loop is a measure of the thermal fatigue damage that will occur. <7>

II. MATERIALS AND METHODS

Five high-chromium cast iron rolls from different manufacturers which had prematurely failed within a six-month period were subjected to failure investigation. Details of the investigation consisted of the following:

a. macro-analyses and photographic documentation of the fracture surface and other suspicious areas (i.e., areas of firecracking) to locate the origin of fracture
b. review of roll history of adverse or abnormal conditions in the mill prior to failure
c. metallographic examination of spalled samples

III. Discussion of Results

3.1 Macro-Analyses and Roll History

Shown in Table 1 are the results of macro-analyses and history of abnormal rolling conditions to ascertain the origin and cause of failure.

Table 1

Fracture Surface and Its Origin/Cause of Failure

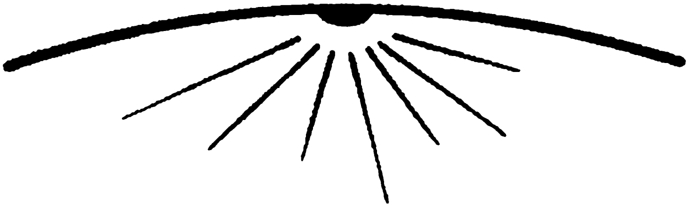
Roll	Description of Fracture Surface	Origin of Fracture	Abnormal Rolling Condition Prior to Failure	Cause of Failure
A	Barrel breakage oriented about 60^0 from the roll axis	Surface	Clogged Nozzles of Cooling System	Thermal Stress*
B	Light spalling from shell	Surface	Cobble	Rolling Stress
C	Light spalling from shell	Surface	Low tail end temperature	Rolling Stress
D	Barrel breakage oriented perpendicular to the roll axis	Surface	Clogged Nozzles of Cooling System	Thermal Stress*
E	Knife-cut fracture oriented perpendicular to the roll axis	Center	Normal	Residual Stress

*firecracking on the roll surface along broken face

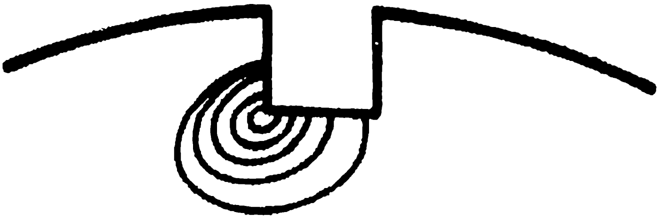
Rolls A and D

Shown in Figure 4 is a typical photograph of the mating fracture surfaces of a barrel breakage which occurred in rolls A and D. This is also known as thermal breaking. <8> A planar view which represents the fracture surface of either roll A or D is also shown in Figure 4a. Radial marks which point to the fracture origin located at the surface (at 7 o'clock) of the roll are distinguishable. Certain fracture features aid in locating the failure-initiation site in broken rolls as shown in Figure 5. <9>

The origin of fracture was a firecrack at the roll surface which is a result of plastic deformation from thermal fatigue cycling and has propagated into the roll in the radial direction. Among many firecracks developing in the surface region, there are only a few that grow into fatigue cracks and further grow to result in roll failures. <10>



(A) Radial marks emanating from the fracture origin.



(B) Beach marks spreading out from the fatigue fracture origin(often seen at corners of keyways and within spalls).

Figure 5. Fracture features which aid in locating the failure-initiation site

The force which causes cracks on the roll surface to propagate to the inner part of the roll is mainly bending stress. This is due to the axial bending of the roll. When firecracks are fine and evenly distributed, individual firecracks receive a smaller share of the resulting stress, but when firecracks are coarse and uneven, individual firecracks are subjected to larger share of stress which leads to quicker fracture propagation. <10>

The barrel breakage, therefore, in rolls A and D was likely caused by relatively coarse and uneven firecracks which occurred on the roll surface along the fracture surface as shown in Figure 6.

In both rolls A and D, the barrel breakage occurred at a time after the nozzles of the cooling system were clogged, thus resulting to an insufficient coolant volume. It is the nature of high-chromium cast iron rolls to be sensitive to burning during periods of insufficient cooling which has a detrimental influence on thermal fatigue. This is due to its heat conductivity being twice as weak as that of steels for hot working in view of a large proportion of M_7C_3 eutectic carbides. <11>

Rolls B and C

Shown in Figure 7 is a typical spalled surface which occurred in rolls B and C. Small spalls are caused primarily by localized overloads such as cobbles and cold strip ends in which the impact affects mostly the surface of the roll.

Spalling is a fatigue phenomenon due to a combination of mechanical and thermal stresses.<9> Apart from causing overloading, these cobbles and cold strip ends result to a brief period of localized overheating because of the stationary contact. Longitudinal cracks are then formed which develop deeper and deeper in the course of rolling and eventually culminate in spalling.

As shown on Figure 7a which is a closer view of the spall surface, the propagation of beach marks (slant region of fracture surface) is towards the roll surface at the bottom portion. While it would appear at first glance that spalling has initiated from the inside (underneath the upper roll surface), it has actually started from the upper roll surface as shown by the propagation path (cliff area which is a flat region normal to the roll surface). It should be noted that if the fracture surfaces show both flat and slant fractures, it is the flat fracture region which is generally considered to occur first. The fracture-origin site is usually characterized by a total absence of slant fracture or shear lip. <9> Also, longitudinal cracks on the roll surface can be seen immediately above the origin of spalling.

Thus, the cause of failure is another surface problem due to firecracking. Spalling proceeds from the surface inwards approximately towards the radial direction and afterwards propagates towards the surface in the opposite direction as manifested by the beach marks.

Roll E

Shown in Figure 8 is a planar view of roll E with very fine radial marks which are not quite distinguishable as having emanated from the center of the roll and subsequently propagated towards the periphery. For roll E, the barrel breakage has started from the core. While a certain amount of thermal stress which leads to fine and evenly distributed firecracks cannot be totally avoided, this has been superposed most likely by residual stress since there was no abnormal condition prior to failure. This residual stress is inherent in the manufacture of high chromium iron rolls because of faulty heat treatment and is the most likely cause of failure except when the roll is not sufficiently cooled or otherwise properly operated.<8> However, this has not been verified experimentally.

3.2 Metallographic Examination of Spalled Samples

Fractured surfaces of the spalled samples were so badly rubbed-off that fractography could not be carried out. Shown in Figure 9, however, is the shell microstructure of a high-chromium cast iron roll. For this roll chemistry, chromium substitutes for part of the iron in Fe_3C, and the primary and eutectic carbide, M_7C_3, solidifies to comprise as much as 40% of the microstructure. <12> At lower temperatures, secondary carbides, $M_{23}C_6$, M_6C and M_2C precipitate out to mask the matrix which is lower bainite and martensite. <1> These fine carbides give excellent abrasion resistance to high chromium rolls.

Shown in Figure 10 is a firecrack which nucleated at a carbide phase normal to the working surface of the roll (top of picture) and has propagated into the radial direction. Carbides play an essential role in the cracking process since they are prone to breakage due to their low tensile strength.

IV. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

Firecracking is a major problem in high-chromium cast iron hot mill rolls since it greatly limits their service lives. It is a deterioration on the roll surface characterized by a fine fire crazing pattern which is a manifestation of thermal fatigue.

a. Coarse and uneven firecracks brought about by careless cooling practices serve as stress risers and hence failure initiation sites for barrel breakage.
b. Localized overloading due to cobble and low tail end temperature results to mechanical stresses and detrimental firecracks from thermal stresses which eventually leads to light spalling from the shell.
c. Firecracks nucleate at a carbide phase normal to the roll surface and propagate into the radial direction.

4.2 Recommendations

In order to minimize the detrimental effect of thermal fatigue in the working lives of high-chromium cast iron hot mill rolls, the following are recommended:

a. To reduce the thermal fatigue damage, the water cooling system must be designed in such a way that heat is extracted as quickly as possible without chilling the surface significantly below the average roll temperature to minimize the tensile plastic deformation.

b. Frequent checking of cooling system especially nozzles and filters should be observed to avoid high thermal stress brought about by roll coolant trouble.

c. Close monitoring of the roll surface should be made to find as early as possible detrimental coarse and uneven firecracks. It is essential to remove all remnants of these firecrakers by roll dressing as thoroughly as possible. A dye-penetrant-test could be performed on the roll surface after dressing or a high-precision eddy-current flaw detection test could be applied every time a roll is dressed. <3> <8>

d. When jamming of strip occurs as in stoppages, cobbles, etc. the following should be observed: <9> The cooling water should be shut off, the rolls separated, and the contact between strip and roll minimized.

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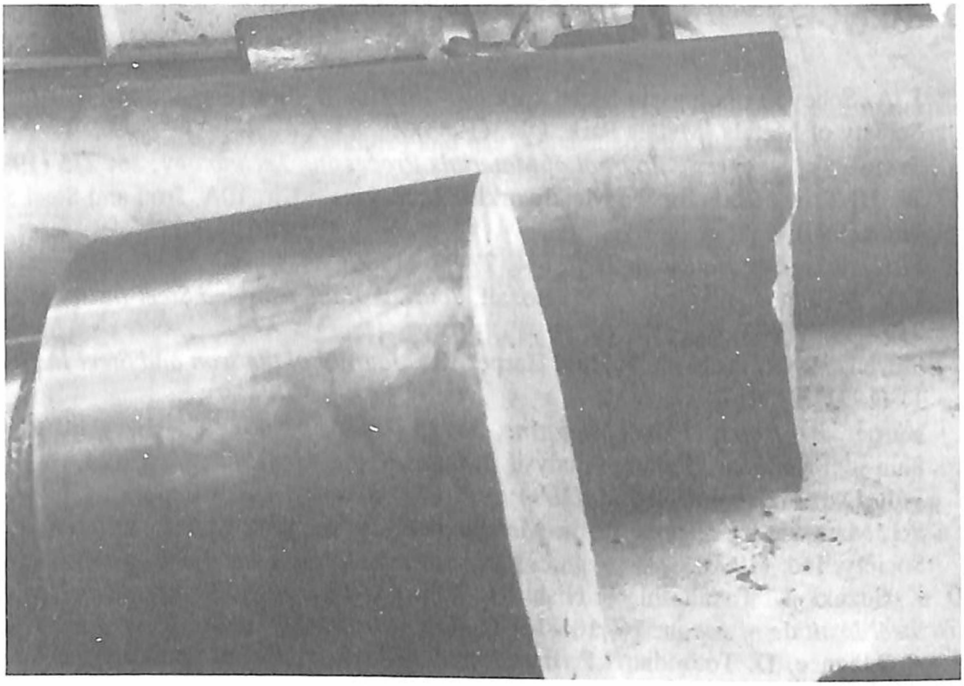

Figure 4. Mating fracture surfaces of a barrel breakage

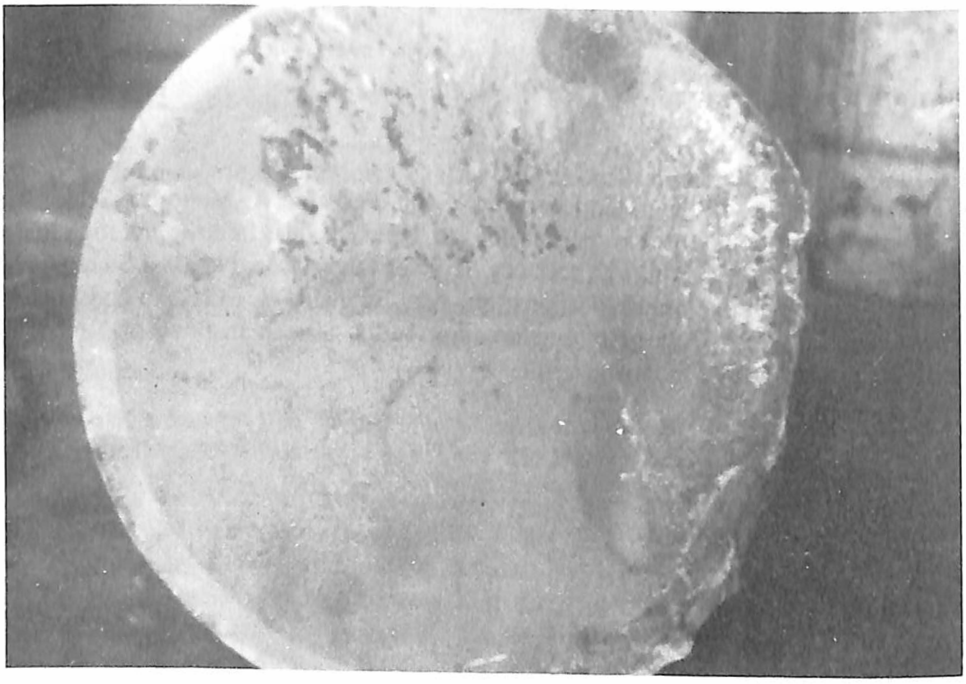

Figure 4a. Radial marks emanate from the origin of fracture which is located at the roll surface (about 7:00)

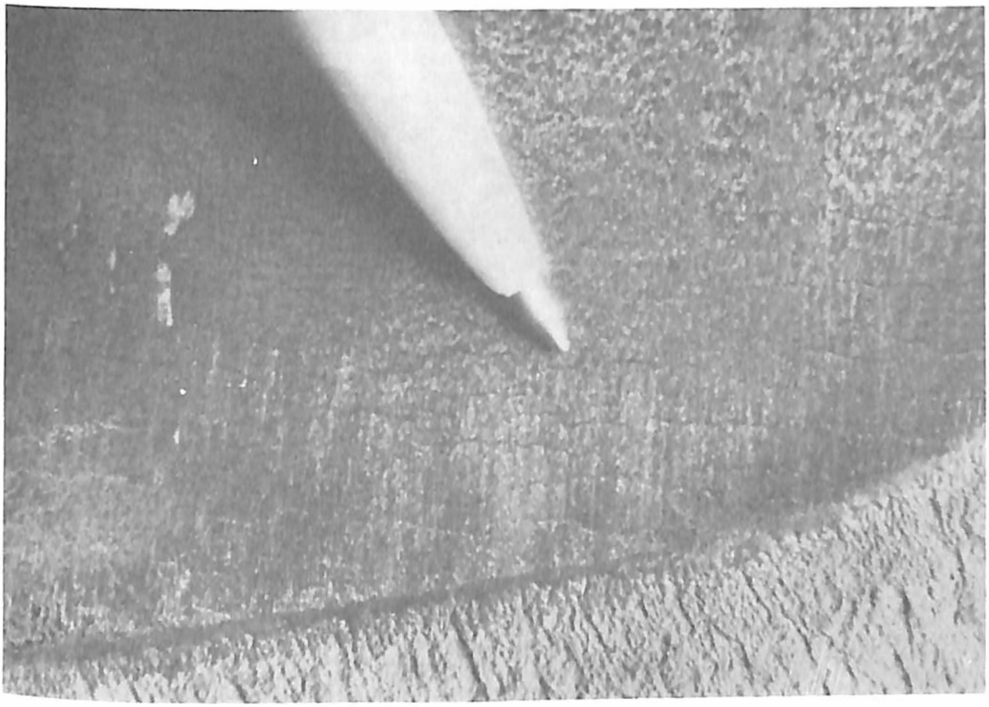

Figure 6. Coarse and uneven firecracks on the roll surface along the fracture surface

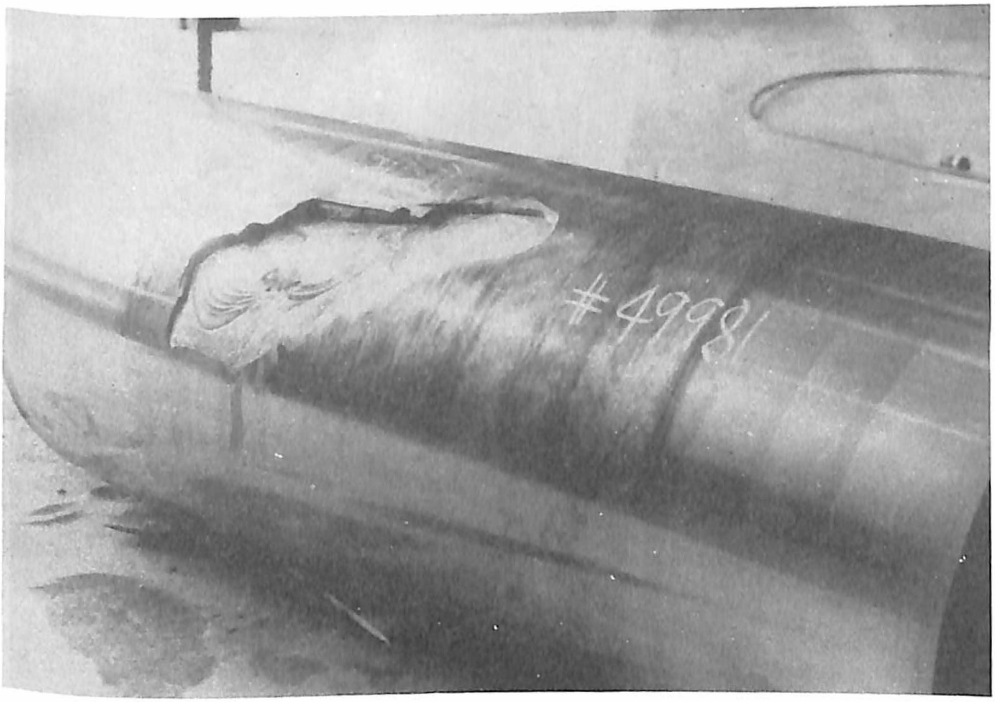

Figure 7. General view of light spalling from shell as a result of overloading

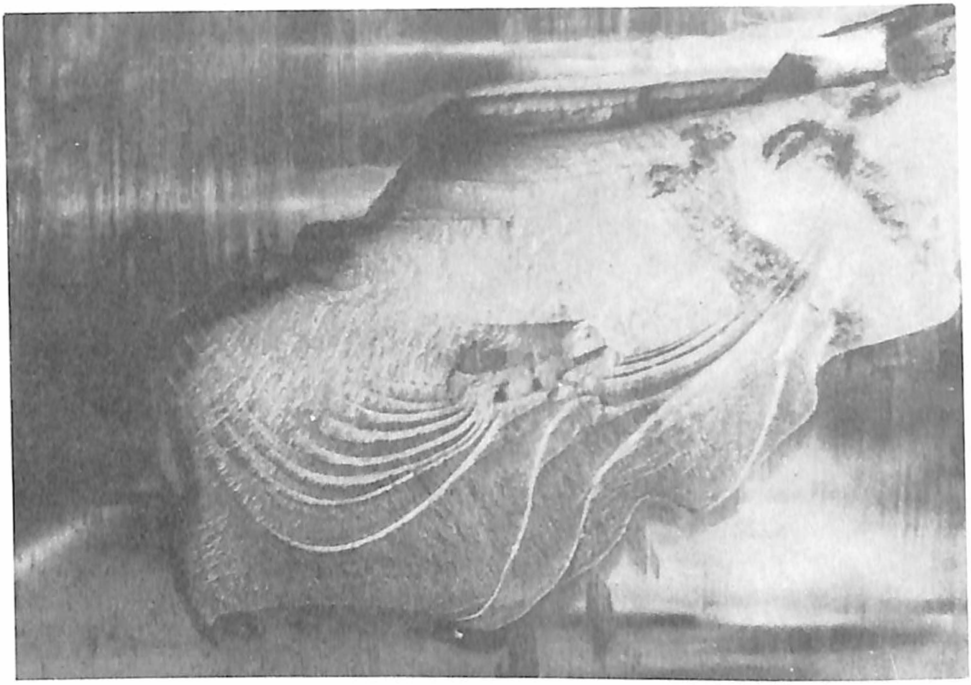

Figure 7a. Closer view of spalled surface revealing origin of spalling and propagation of beach marks

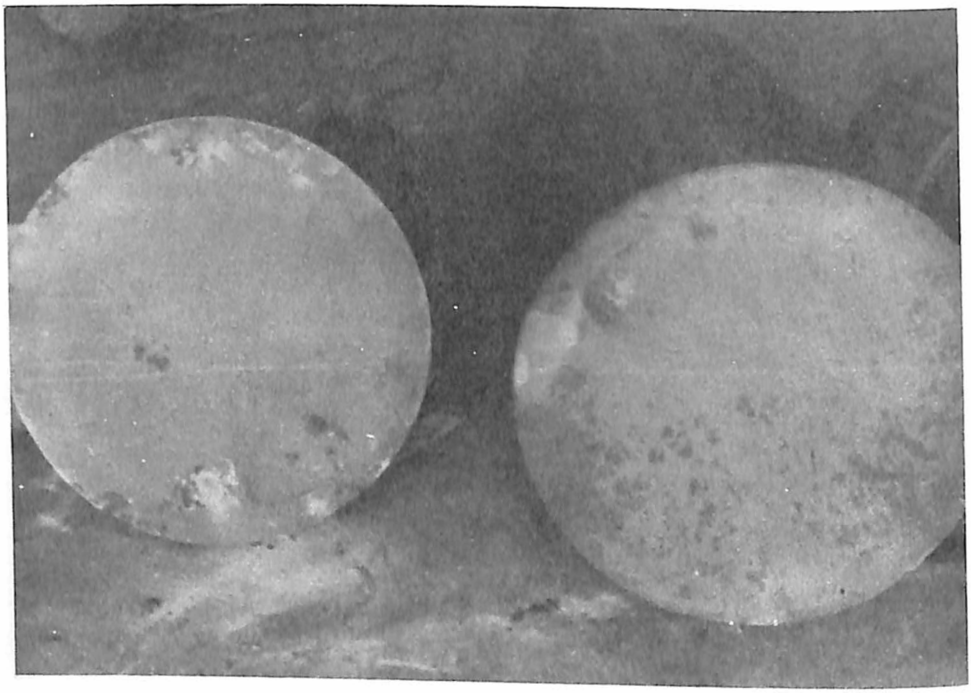

Figure 8. Very fine radial marks emanate from the center and propagate towards the periphery

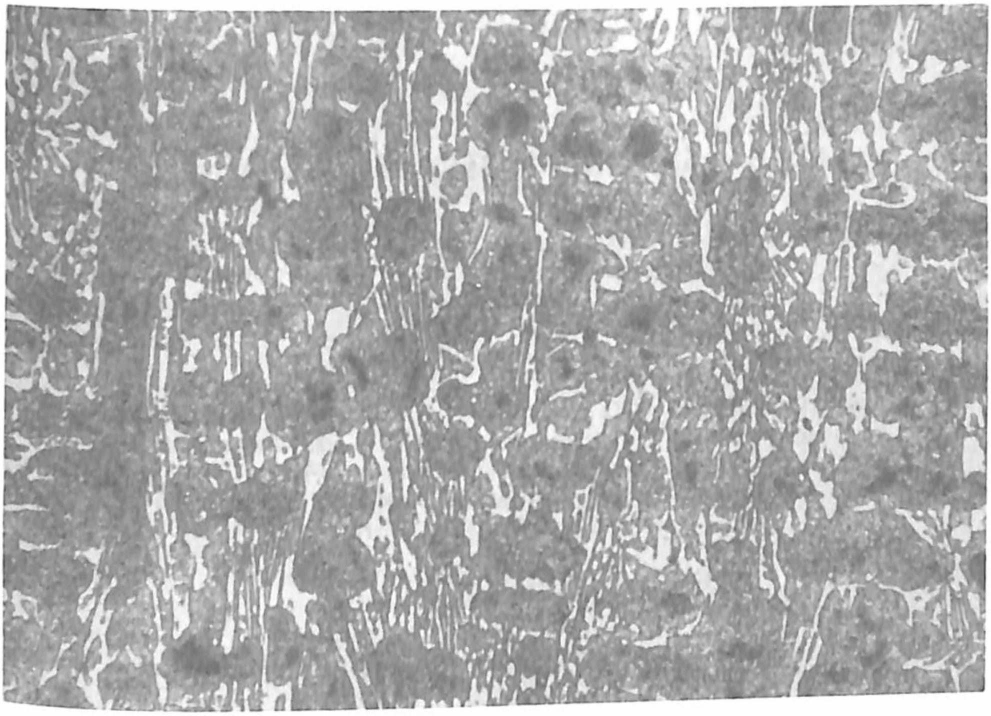

Figure 9. Shell microstructure of a typical high chromium hot mill roll

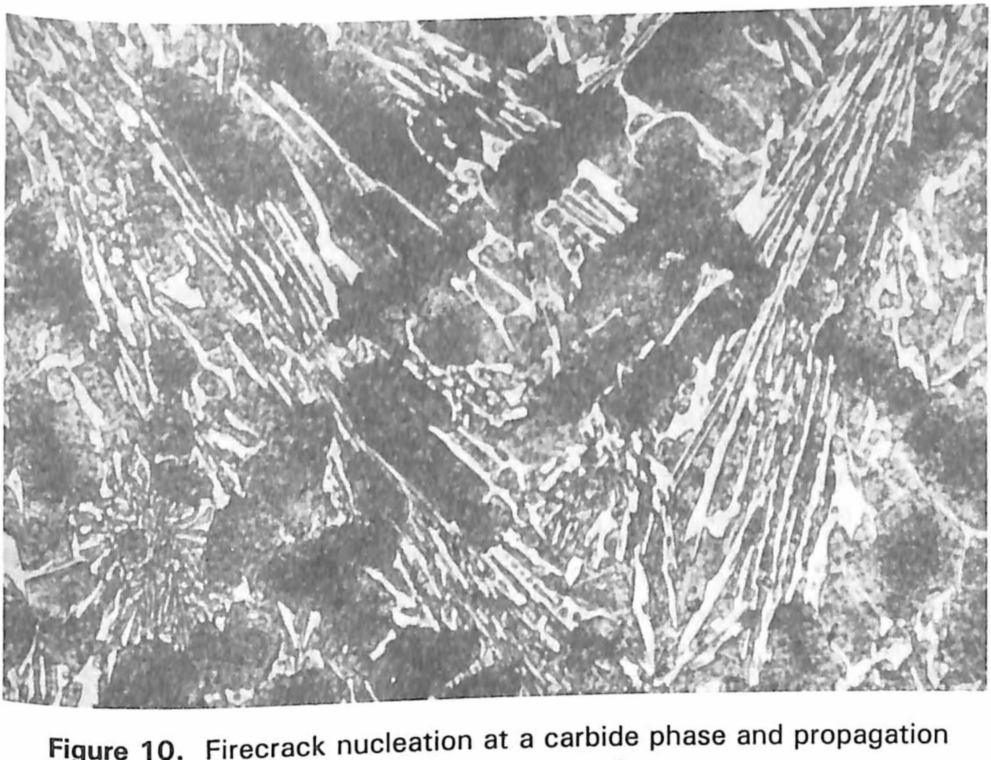

Figure 10. Firecrack nucleation at a carbide phase and propagation normal to the roll surface