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Failure investigation of forming rolls made of Si_3N_4

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Abstract. Tool surfaces for the forming of shaped steel strips are typically made from cemented carbides. Disadvantages of these tools are that they suffer from roughening of the surfaces and severe wear, which deteriorates the surface quality of the products and restricts the lifetime of the tool. Due to their high hardness and better high-temperature properties, improvements of tool behaviour can be expected by the use of silicon nitride.

During a collaborative project between industrial partners, universities and research centres, forming rolls made of silicon nitride were tested at several positions in rolling mills. The suitability of Si_3N_4-rolls in rolling mills could be demonstrated at low and medium hard loaded positions. At Böhler-Profil in Waidhofen/Austria the rollers were used for the preparation of shaped steel strips from blank feedstock. During this very severely loaded application a pair of rollers failed. It could be shown that the rolls failed due to thermal stresses which can be reduced to a large extent by an improved design.

Introduction

Ceramic materials have high hardness, low-friction coefficients, good chemical stability and excellent high-temperature properties. Due to these properties the use of ceramic materials for rolling applications has been investigated in the last two decades [1-7]. One advantage of the use of silicon nitride tools in rolling mills is that the lifetime of the tools is longer. Furthermore, products like rolled wires have a better surface quality [3, 4].However, failures of rollers in different applications have been reported (e.g. when materials with a very high deformation resistance were rolled [4-7]).

Macroscopic and microscopic investigation [9]

Fig. 1 shows the failure in the rolling mill at Böhler-Profil. The silicon nitride ring is 50 mm wide, has an outside diameter of 350 mm and an inside diameter of 280 mm. The ceramic rings are clamped between a ring flange and a fixed flange (hub), both made of high grade steel. The ring flange is bolted down onto the hub using eight 8 mm socket head screws. In application the roll pressure can reach 60 tons, and the temperature of the rolled wire is between 600 °C and 800°C.

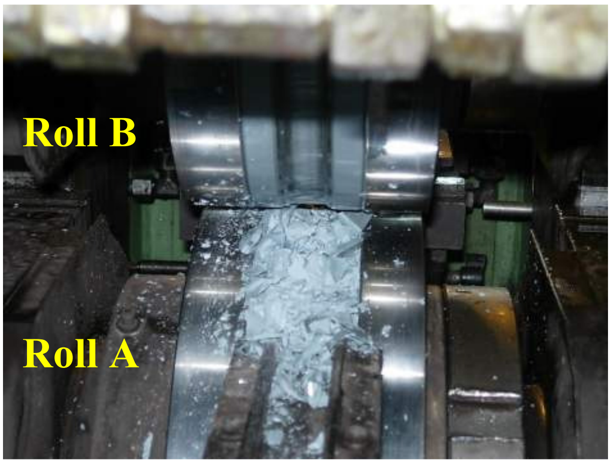
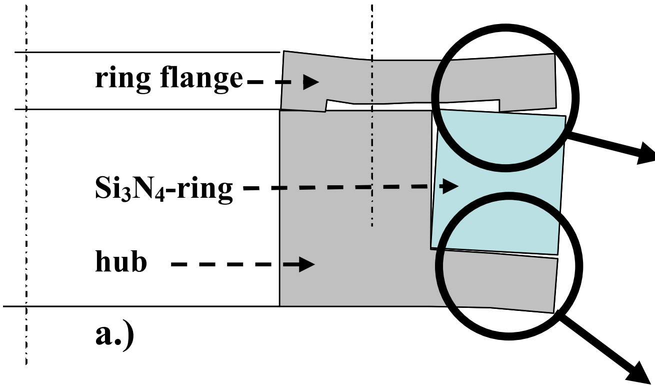


Fig. 1: Forming rollers after fracture (photo: Böhler)

One roll (A) has completely shattered into a few large and many small fragments, the second roll (B) has failed from a single spalling fracture.
In both rolls (A and B) the pattern of metal contact with the ceramic was the same. From the sketch of the clamping of the roll (Fig. 2a) can be recognized that the clamping was not uniform. There is a narrow band of contact on the ring flange side (Fig. 2b). On the other side (the hub side) it can be seen that there is primary contact over an area about half the radial width of the roll (fig. 2c). On the inside surface of the roll metal transfer onto the machined surface profile can be seen.



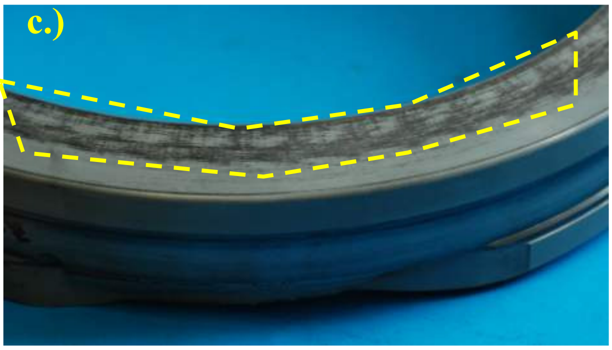


Fig. 2a: Sketch of the clamping of the roll after tightening the screws. When the screws are tightened the ring flange distorts and bends slightly. The hub is forced also to bend outwards.

Fig. 2b: Contact zone with the area of metal clamping in roll B. The narrow band of contact can be seen in the middle of the roll (arrows).

Fig. 2c: Opposite side of roll B with the metal contact zone (marked by the dashed polygon).

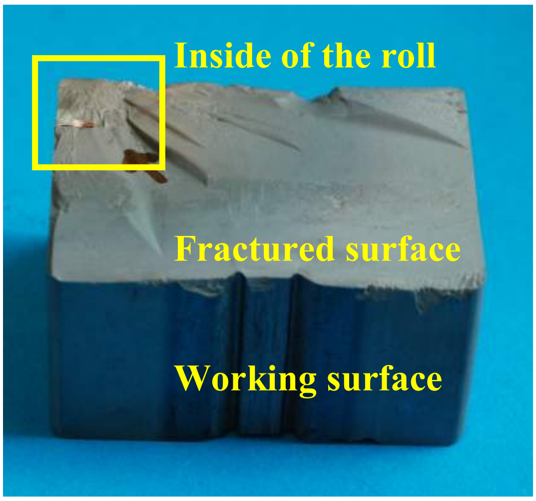


Fig. 3a: Macro-view from fractured piece No. 1 after coating for a SEM-examination. The mirror can be found on the inside surface near the edge (rectangle).

In Roll A, among the extensive fragmentation a clear transverse fracture was found (Fig. 3a). In the stereo microscope a clear semicircular mirror can be seen (Fig. 3b).

The large-sized chip (marked by an arrow) is a secondary edge chip. The area where the fracture origin is situated is marked by a rectangle. In the SEM a porous region below the surface (Fig. 3c) was found, but this area seems too small to act as a fracture origin. Therefore it is thought that the fracture origin may be a hoop loaded machining crack.
If the mirror constant [8] is estimated as 8 MPa $m^{1/2}$, the mirror radius indicates the stress at fracture was about 250 MPa.

On other fragments further principle transverse fracture surfaces could be found, but all with indications that they too were produced by cracks propagating radially outwards (not here shown).

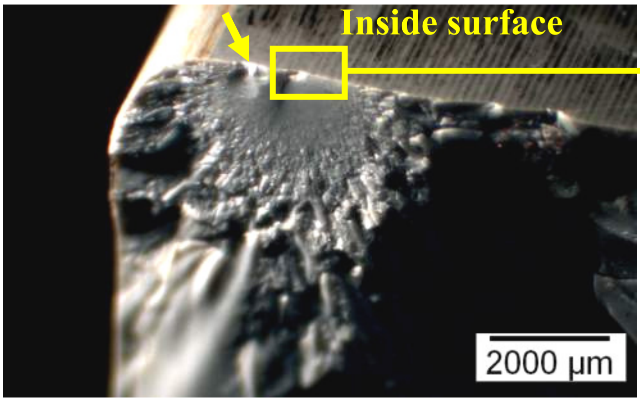


Fig. 3b: Part of the fracture surface of fragment 1 with the mirror in the stereo microscope.

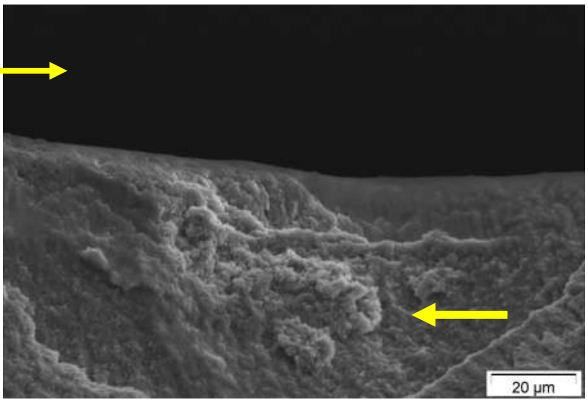


Fig. 3c: SEM-micrograph of the fracture origin. The porous zone (arrow) below the surface seems to be too small to act as a fracture origin.

Investigation of these further fragments showed them to be high-energy fractures which started at the inside surface corner. This group of fragments shows characteristics typical of flexural failure i.e. with compression curl. This kind of failure is secondary and resulted from the opening of the ring after primary fracture and its fracture into several fragments.

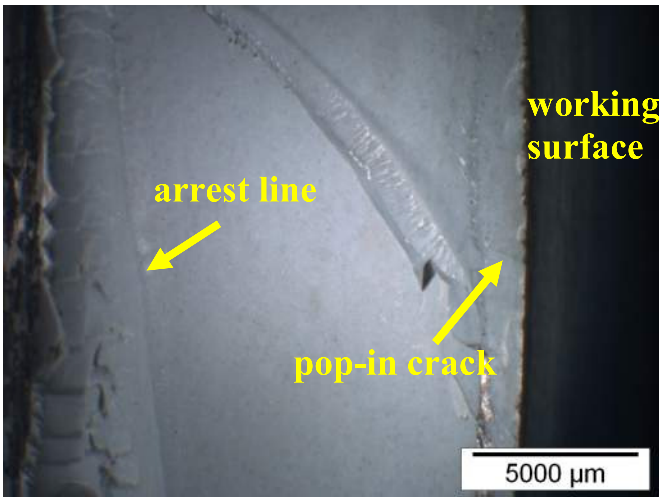


Fig. 4: Detail of the right hand flake of roll B.

In contrast, Roll B has failed non-catastrophically by the production of two flakes which commenced from the radii at the profile sides in the working face. The crack morphology suggests that the flakes developed from a short pop-in crack in the side of the profile over several cycles of loading and then final broke off across the short ligament of remaining material near the contact line on the side of the ring flange side.

Fig. 4 shows a detail of the right hand flake. Here the region of pop-in from the corner of the profile is still visible.

Discussion

Roll A: The failure of Roll A is not a consequence of cracks introduced by metal contact through the forming process. The reason for the failure is the occurrence of hoop tensile stresses around the inner surface of the roll. After the principal transverse fracture, the opening of the ring resulted in fracture into several large fragments. The final fragmentation seen in Fig.1 would result from there being several dislodged large fragments interfering with the rolling process.

There is a strong probability that the hoop tensile stresses causing the initial radial fracture are due to thermal expansion mismatch between the hub and the roll. If the designed clearance between the hub and the ceramic part is insufficient, a general rise in temperature of the entire hub system in service might result in closure of the gap followed by the application of an internal bursting pressure on the roll. The expansion coefficient mismatch between the metal hub and the ceramic is about 13 x 10^{-6} °C^{-1}. If the clearance is 0.05 mm (this is typical for other systems) the temperature rise to close the gap on a 140 mm inside radius would be only $0.05/(140 \times 0.000013) \approx 27$°C. For greater temperature rises most of the extra mismatch would go into stressing the ceramic. A temperature rise of 100°C can be estimated to cause a hoop stress of around 200 MPa in the ceramic compared with the stress at fracture by a mirror analysis of approximately 250 MPa.

Roll B: The mechanical forces developed during the rolling process are high and the roll can move relative to the flanges and the hub. The high forging force will push the two rolls against their respective hubs, but the stresses developed are principally radial compressive.

However, on the periphery of the contact zone large tensile stresses are expected to occur. Hertz calculated these stresses between a sphere and an infinite half plane [10, 11]. Such stresses were analysed with a 3D-FE model in [6, 7]. It was found that the Hertzian stresses, which can reach about 1/6 of the mean compressive stresses, occur near the surface and decrease rapidly in the depth. Therefore, for short surface cracks the stress intensity factor reaches a maximum and decreases for longer cracks. As a result of this behaviour pop-in cracks come into being but stop after a short distance. Unless these unavoidable pop-in cracks are pinned by appropriate lateral stressing they can develop into edge flakes.

Conclusions

There exist two distinct types of roll failure. Nevertheless it would be possible to increase the service life of the rolls with two simple modifications:

1. To reduce the risk of hoop tension break-up the room-temperature clearance between the roll and the hub should be increased by an amount sufficient to allow the closure of the gap during heating the working hub temperature.
2. The second modification is to the flange designs in such a way that axial clamping onto the ceramic roll takes place preferentially at the outer edge of the roll. The flange contact regions have to be suitably profiled to allow for the inevitable elastic distortion. Then the axial compressive force could be maximised across the roll outer surface, and not well below it as at present. This should help to restrict the propagation of cracks from the profile corners and prevent flakes from developing and breaking off.

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