Analysis of the failured pinion from the drive of a cement mill

Analiza poškodovanega pastorka iz pogona mlina za cement

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Abstract: The pinion from the drive of the cement mill was failure. The teeth ruptured and peeling occurred on the sides of some teeth. The failure was only located on one side of the pinion. This type of failure is common with surface-hardened gears.
We have found that the failure of the pinion is a direct consequence of the incorrect geometry of the surface hardened layer. The lifespan of the pinion could have been extended if the whole surface of the faces and roots of the teeth had been hardened and if the hardening had been deeper.

Povzetek: Na pastorku iz pogona mlina za cement so nastale poškodbe v obliki prelomov in luščenja na bokih nekaterih zob. Poškodbe so bile locirane le na eni strani pastorka. V okviru izvedene analize smo ugotovili, da so poškodbe pastorka posledica neustrezne geometrije površinsko kaljene plasti. Trajnostno dobo pastorka bi zanesljivo podaljšali, če bi bili boki in koreni zob kaljeni v celoti in če bi bila površina globlje kaljena.

Key words: cement mill, pinion, failure analysis, surface hardening
Ključne besede: mlin za cement, pogonski zobnik, analiza poškodb, površinsko kaljenje

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Introduction

In our work we describe a relatively common example of the rupture of gear teeth of a relatively large module of large dimensions that - built into reduction gears of large machinery and devices in process industries (e.g. cement mill) - also endures large loads, forces and torques.[1, 2]

When manufacturing gears for large modules, wear of the gear teeth faces is often prevented by surface hardening.[3, 4] Little attention is usually paid to the resistance of gears against fatigue. When it comes to gear fatigue, the division, signs and amount of internal stresses acquired specifically through surface hardening are very important. The incorrect geometry of the hardened surface is the cause of improper internal stress distribution and inadequate structural strength.[5]

With gears, the hardened surface area of the teeth faces often ends near the root of the teeth. Consequently, this hardened area is where positive (tensile) internal stresses occur. This is normally also the area of the largest changes of external tensile (positive) stresses. The superposition of positive stresses from both sources, in connection with additional eventual geometric stress concentrators, contributes to the formation and spread of fatigue cracks. However, since the gears frequently rotate in both directions, cracks appear in both roots of a tooth, of which one crack is usually longer.

The failure of the pinion of the cement mill drive (No. 354881, teeth 28, module 36, diameter 1640 mm, width 1800 mm) occurred in the form of fatigue cracks and the peeling of steel on the faces of several teeth. The failure was only located on one side of the pinion (Figure 1). The teeth breakage began with ruptures, which typically started at the roots of the teeth faces and spread outwards. The breakage resulted in transverse ruptures along the height of the teeth.

The other failure that occurred was the peeling of the steel on the faces of the teeth. Such failure is caused by excessive Hertzian pressure applied to the faces, or is a consequence of the lack of compressive strength of the steel at a critical depth of the teeth surface. In this way, the unbroken teeth are also failured, but the extent of this type of damage was significantly smaller in our case.

Failure analysis

Visible lines formed on both side faces of the individual teeth and their roots. They are a consequence of the thermal effects of surface hardening.[6] These lines were wider and more distinctive

Figure 1. Failure of the pinion: part of the broken off tooth, and the peeling of steel on the faces of the teeth

Figure 2. A broken tooth and two unbroken teeth with a fatigue crack (left). Two failured teeth: the lines indicating the heated surface (right).

Table 1. Chemical composition of steel pinion [12]

Element	C	Si	Mn	P	S	Cr	Mo	Ni
(mass fraction, *w*/%)	0.40	0.34	0.69	0.01	0.03	1.16	0.27	0.28

at the undamaged side of the gear.[7, 8] The hardened areas were along the faces and at the roots (Figure 2), and were interrupted at the top of the teeth.

The teeth faces on the failured side were macroscopically etched.[9] This revealed the surface hardened layer, the macroscopic average thickness of which is approximately 1 mm, which generally starts at the top of the tooth and ends approximately 10 mm above its root. The macroscopic profile of the teeth's surface hardened layer is not satisfactory. It has two disadvantages: it only covers a part of the teeth faces, and it is very thin. The entire surface of the faces and roots should have been hardened; it is not necessary to harden the surface at the top of the teeth. The macroscopic characteristics of the surface areas of the ruptures show that the ruptures are a consequence of the fatigue of the steel.[10, 11]

The chemical composition of the steel of the pinion is shown in Table 1. According to its chemical composition, the steel of the pinion corresponds to the high-strength steel used for improving VCMo140 of the Slovene steel manufacturer Metal Ravne.[12]

The microstructure of the pinion steel reveals that the pinion was previously strengthened and its surface was hardened (Figure 3).

The microstructure of the steel at the core of the tooth consists of tempered bainite and ferrite. On the faces of the teeth, where the steel surface is hardened, the microstructure consists of martensite (Figure 4). The martensitic microstructure of the hardened surface transforms through a binary microstructure consisting of martensite and areas of tempered bainite and ferrite into the microstructure of the core. The hardened surfaces and the area of transition to the core have a normal microstructure.

The constant hardness (approximately 650 HV) is characteristic of the hardened surface of the pinion, and gradually decreases over a transition zone to the hardness at the tooth core (approximately 275 HV) (Figure 5).

CAUSE OF FAILURE

The initial teeth ruptures started at the point of transition from the faces to the roots of the teeth. There, the changing loads are large enough to initiate the start and spread of fatigue cracks. A contributing factor is the relatively low strength (tangential stress) of the steel in the area (approximately the same hardness and strength as at the core of the teeth), and internal stresses that are – due to the incorrect geometry of the hardened surface – unfavourable in the area (positive, tensile) and increase the overall level of stress applied.[13]

In the hardened surface there are typically internal tangential stresses, and in its proximity also tensile stresses. This generally has a beneficial effect on the sustained dynamic strength, or fatigue resistance. For the given example, we can only estimate that the internal stresses in the area where the fatigue cracks first appeared were positive, and that they were unfavourably added to the external, operating stress.

The geometry of the hardened surface does not contribute to the improvement of the permanent dynamic strength of the teeth, but rather diminishes it. The correct geometry of the hardened surface is such that the whole area at the faces and roots of the teeth is hardened (without discontinuities). The areas of the heated surface at the faces of the pinion teeth

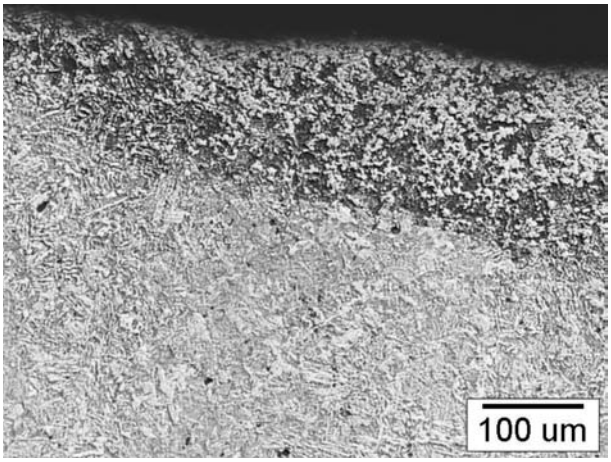

Figure 3. The area where the hardened surface of the tooth ends (OM)

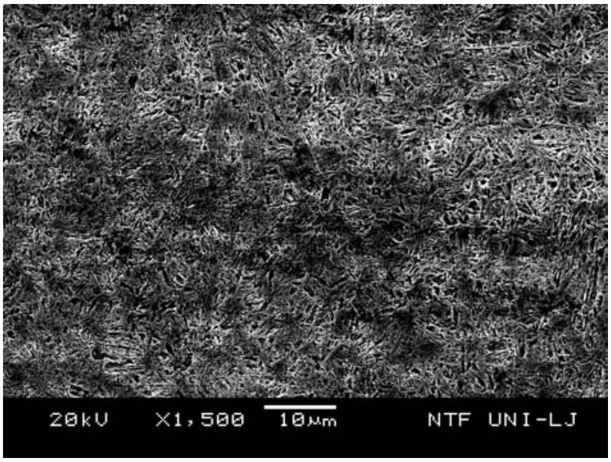

Figure 4. Microstructure of the steel at the hardened surface: martensite (SEM)

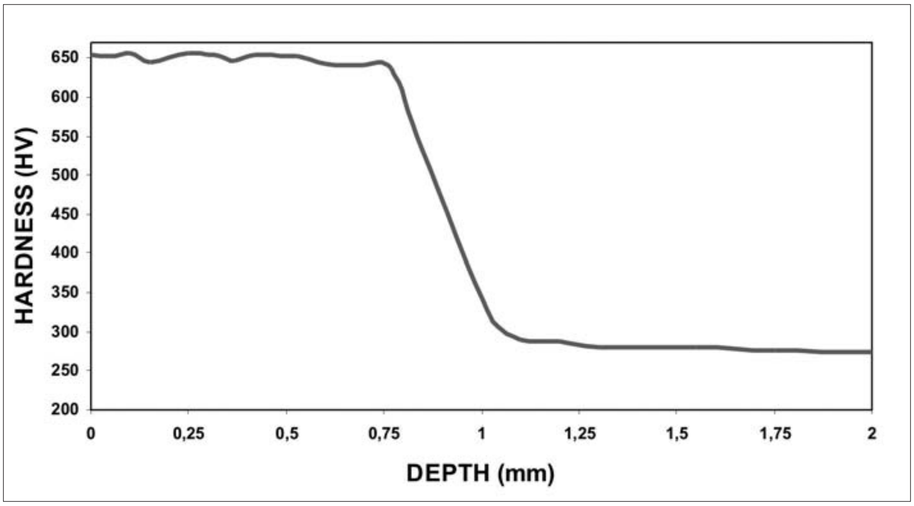

Figure 5. Microhardness in the hardened surface and transition to the core

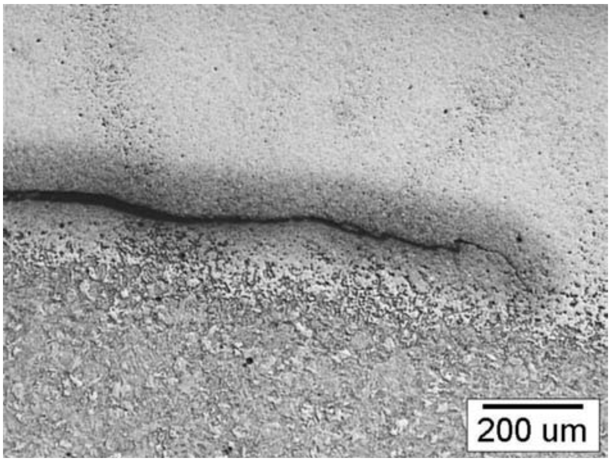

Figure 6. Crack at the point of transition from the hardened surface to the core (OM)

show that the planner and performer of the surface hardening knew this fact, but failed to strengthen the gear teeth correctly. The incorrect geometry of the hardened surface is the cause of fatigue breakage of the pinion's teeth.

The peeling of the steel on the teeth faces is a consequence of excessive Hertzian pressures, which exceed the compressive strength of the steel. The critical area where the cracks and peeling first occurred is at the point of transition between the hardened surface (martensite) and the core of the tooth, where the mechanical properties of steel (strength) begin to decrease rapidly (Figure 6).

CONCLUSIONS

The failure of the pinion (fatigue ruptures of the teeth and the peeling of steel on the faces of the teeth) are a consequence of the incorrect geometry of the surface hardened layer.

The teeth broke off due to fatigue. The ruptures first appeared at the bottom part of the faces at the root and spread outwards, while the breakage resulted in a cross-break along the height of the teeth. The other failure that occurred was the peeling of the steel at the faces of the teeth. Thus, in addition to the ruptured teeth, the remaining teeth were also failured. However, the extent of these failure was smaller. We could therefore extend the lifespan of the pinion if the entire faces and roots of the teeth were hardened, and if the surface hardening was deeper.

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