CRACKS INITIATION IN HEAT-TREATED AND GROUND STEEL

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On the bearing pins of engine crankshafts cracks have appeared during the grinding process. According to some explanations this is due to the unsuitable quality of steel since during the forging process the steel from the billet centre comes to the surface. A number of engine crankshafts and bars forged from high and low quality billets were investigated to find out the role played by the metallurgical quality of steel in this phenomenon. At the same time the conditions of surface quenching and grinding were being changed within a relatively broad range to be able to establish the effect of these parameters on cracks initiation. A detailed metallographic analysis was conducted on all specimens. On the basis of the obtained results the metallurgical quality of steel could be with great reliability excluded as an objective factor for surface cracks initiation during the grinding process. By an analytical model the stresses after surface hardening and after grinding were estimated. The findings of the metallographical analysis that cracks initiate only on shallow, hardened surfaces on which due to over-heating during the grinding process hardness is considrebly reduced have been confirmed by the calculation model.

INTRODUCTION

An important part of motor vehicles are engine crankshafts. The manufacturing process of heavy lorry engine crankshafts includes forging of billets from CrMo steel, mechanical and heat treatment, surface quenching and grinding. The quality of steel and the crankshafts is carefully controlled in all manufacturing steps. However, damages often appear also during the final grinding process destroying all the previous work put into it. In the present forging process the steel flows so that the bearing pins are reached by the steel from the billet centre. This steel from the billet centre is of lower metallurgical quality. This was one of the main reasons that frequent crack initiation during the forging process or heat treatment and especially during the grinding process had been attributed to low steel quality, (1).

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The purpose of our investigation was to find out the real effect produced by the steel quality on crack initiation during the grinding process. This was done so that in the investigations we used steel of high and unaccebtable low quality. The purpose of choosing billets from unacceptable steel quality was to make the defects appearing during the manufacturing process of the crankshaft, as visible as possible. The selection of the billets was carried out on the basis of the macrostructure on the billet cross section Fig. 1,2 . We managed to select billets of very high, over-average quality and also those whose quality was on the basis of macrostructure estimation, unacceptable for the manufacturing of crankshafts. In the latter we could clearly see central porosity, external shrinkage cavities and liquation square.

The billets were forged into the form of bars having the same diameter as that of the crankshaft-pin bearing. This was done with the purpose to get as large a surface as possible for quenching and grinding. On one of the billet edges such an amount of steel was removed that the steel from the centre, i.e. from the liquation square, came to the surface.

2. INVESTIGATION PROCEDURE

The billets on which one edge was removed to the depth of the liquation square, were forged into bars of such a diameter that turning of separate segments with the diameter approx. loo mm and equal length as that of the bearing pins (approx. 32 mm) was possible on them.

The forged bars were quenched in oil from the temperature 850°C and tempered on the temperature of 560°C. On the bars separate segments were then turned whose diameter and length corresponded to the crankshaft pin bearings before surface quenching. For these segments the same quenching procedure was used as for the surface of the pin bearings. During the procedure we changed the power and time of surface heating so as to get a varying thickness of the quenched surface layer on the segments. The surface heating times were 8 ... 11 s, the highest temperatures on the surface were 820 ... 900°C, and the depth of quenching 3 ... 4 mm. After the surface quenching the bars were annealed on the temperature 200°C. The surface of the segments was then ground on a machine for external round grinding of the producer Milacron-Cincinnati by various grinding wheels. The grinding wheel diameters were 900...1015 mm, circumferential speed rates were from 35...42 ms^{-1}, segments diameter 100 mm, angular velocity of the bars 0,5...1 ms^{-1}, duration of the grinding process 10...60 s, depth of grinding along the segment cross section 0,4 mm.

The lowest speed rates correspond to those which are technologically prescribed for grinding of bearing pins, the others are higher even upto 6-times. Besides this we also changed the intensity of surface cooling during the grinding process and the frequency of dressing of grinding wheels.

The number of the investigated segments was approx 90. Cracks were searched for by the aid of magnetoflux.

In the investigations we used metallographic, macro-and microscopic methods, hardness measuring, and microanalysis.

A thermo-elastic model for surface quenching and grinding of the segments was realized, introducing analytical expressions for stresses due to phase transformations and temperature changes, (2,3).

3. RESULTS

In the low quality billet liquation square, central porosity and the rests of shrinkage cavities were extremely well seen. Also on the cross sections of the forged bars it was possible to observe all these characteristics. Non-metallic inclusions in the investigated billets are similar; MnS-inclusions are prevailing, while among the others the most frequent are aluminium inclusions. With low quality billets the inclusions in the centre are larger than in high quality ones. Ohterwise, as regards the type, amount and distribution of non-metallic inclusions no outstanding differences were observed between the high and low quality billets. The amount and type of non-metallic inclusions correspond to the quality and range of application of steel.

On the samples taken from the surface and centre of the billets an analysis of the non-homogeneity of chemical compositon was made. The segregations of the principal alloying elements Cr and Mo were higher in the billets of unchangeable quality.These were also bigger in the liquation square than on the billet surface. The size of segregations remained within the known restrictions for this kind of steel. After the forging and heat treatment processes the segregation amplitudes were considerably smaller. The quenched surfaces did not have the form of ideal rings; on the investigated pin bearings the thickness values were much more variable than on the segments. The form of the quenched surface of the pin bearings was affected also by boreholes. The quenched surfaces of the pins bearing were generally thinner than on the sample segments (Fig.3.. 6).

Some characteristic differences between the individual pin bearings and segments were indicated also by the hardness profile along the quenched surface. These differences are the most distinct in a narrow zone (approx. 150...200 um) right under the surface. In the pin bearings where grinding cracks appeared, the measured hardness values were much lower than in the other part of the quenched surface. On the pin bearings where no cracks appeared the differences in the hardness values were negligeable. On the segments which were ground by the lowest speed rates of the steel removing process, the hardness profiles were quite equal to those on the pin bearings without cracks, i.e. the measured hardness values are practically equal along all the quenched surface. On the segments which were ground with high speed rates, the measured hardness values on the surface (150-200 um) were considerably lower than in the other part of the quenched surface and the hardness curve is practically identical to the hardness curve of the pin bearings with grinding cracks (Fig. 7,8,9).

Microcracks on the pin bearing are intergranular. The majority of them reach the depth of 15o-200 µm. The shortest ones run down to approx. 100 µm and the longest ones to 400 µm deep. This means that the majority of cracks reach the same depth as the fall of hardness due to tempering of steel in the grinding process (Fig. 1o).

On none of the investigated 90 segments forged from high an low quality steel cracks appeared during the grinding process.

4. CALCULATION MODEL

For the quantitative analysis of the reasons for crack initiation on the quenched and ground surface the following calculation model was worked out.

The resultant stress state $\sigma_{\varphi R}$, which appears after the quenching and grinding process on the surface of the segment with the diameter 2b=100 mm, consists of the sum of the following stress states due to heat treatment and grinding:

a) Stress state σ_{φ}^{K}, appearing during the quenching process due to phase transformation from austenite into martensite in the quenched surface layer of the thickness $\delta = b - a$:

$$\sigma_{\varphi}^{K}(T_o) = -\left(\frac{a}{b}\right)^2 \sigma_{o,2}^{K}(T_o) \qquad /1/$$

where $\sigma_{o,2}^{K}(T_o)$ plasticity limit o,2 of the quenched layer at the environmental temperature $T_o = 20^{o}C$

b) Thermal stress state σ_{φ}^{H} appearing in the quenched martensite layer due to cooling during the quenching process. At the quenching temperature the properties of steel can be identified with a visco-elastoplastic rheological model, Fig. 11.

$$\sigma_{\varphi}^{H}(T_K) = \left(\frac{a}{b}\right)^2 \left[\varkappa\sigma_o^H + H_T^H \varepsilon_i^H\right]\Big\{e^{-\gamma(T-T_o)} - \sum_{j=1}^{j=m}(1-K_j)\sum_{i=1}^{i=m_2}\frac{e^{-(\lambda_j t+\gamma T_{\beta i})}}{1-\frac{\gamma}{\lambda_j}T_{\alpha i}}\left[e^{(\lambda_j-\gamma T_{\alpha i})t_i} - e^{(\lambda_j-\gamma T_{\alpha i})t_{i-1}}\right]\Big\}\Bigg|_{T=T_K} = \left(\frac{a}{b}\right)^2 \cdot \bar{\sigma}_{\varphi}^{H}(T_K) \qquad /2/$$

T_K - temperature during quenching when the stress state passes into the region in which Hook's rheological model is valid

$$T_K = \frac{2(1-\nu)}{\alpha\sqrt{3}}\,\frac{\sigma_{o,2}^{K}(T_K)}{E(T_K)} \qquad /3/$$

where

ν - Poisson's number
α - linear thermal expansion coefficient
$E(T)$ - Young's module
$\sigma_{o,2}^{K}(T)$ - plasticity limit o,2 of the quenched layer which is temperature dependent
t - time
σ_o^H, H_T^H, σ_o^B, H_T^B, μ, K_j, λ_j, $\varkappa$ - coefficients determining the properties of the visco-elastoplactic material
$T_{\alpha i}$ - speed of the increase or fall of temperature
$T_{\beta i}$ - temperature at the beginning of the subintervall i
ε_i^H, ε_i^B - intensity of plastic deformation
e - basis of natural logarithms

c) Stress state $\sigma_{\varphi 1}^{B}$, which appears during the grinding process due to martensite tempering. The thickness of this layer is relatively small amounting an average of δ_1=150 µm which can be seen from the microhardness profile on the axial cross sections, (Fig. 7,8,9).

$$\sigma_{\varphi 1}^{B}(T_o) = \sigma_{o,2}^{B}(T_o) \qquad /4/$$

d) Thermal stress state $\sigma_{\varphi 2}^{B}$, which appears owing to the visco-elastoplastic deformation in the segment layer of thickness δ_1

$$\sigma_{\varphi 2}^{B}(T_B) = \left[\varkappa\sigma_o^B + H_T^B \varepsilon_i^B\right]\Big\{e^{-\mu(T-T_o)} - \sum_{j=1}^{j=m}(1-K_j)\sum_{i=1}^{i=m_2}\frac{e^{-(\lambda_j t+\gamma T_{\beta i})}}{1-\frac{\gamma}{\lambda_j}T_{\alpha i}}\left[e^{(\lambda_j-\gamma T_{\alpha i})t_i} - e^{(\lambda_j-\gamma T_{\alpha i})t_{i-1}}\right]\Big\}\Bigg|_{T=T_B} = \bar{\sigma}_{\varphi 2}^{B}(T_B) \qquad /5/$$

where T_B - temperature during grinding where the stress state has passed in the region where Hook's rheological model holds.

$$T_B = \frac{2(1-\nu)}{\alpha\sqrt{3}}\,\frac{\sigma_{o,2}^{B}(T_B)}{E(T_B)} \qquad /6/$$

All the other parameters in equation /5/ are identical to those in equation /2/ except σ_o^B, H_T^B, ε_i^B.

The resultant stress state after quenching and grinding is equal to the following sum:

$$\sigma_{\varphi R}(T_o) = \sigma_{\varphi}^{K}(T_o) + \sigma_{\varphi}^{H}(T_K) + \sigma_{\varphi 1}^{B}(T_o) + \sigma_{\varphi 2}^{B}(T_B) \qquad /7/$$

Taking account of equations /1/, /2/, /4/, /5/ we get:

$$\sigma_{\varphi R}(T_o) = \left(\frac{a}{b}\right)^2\left[\bar{\sigma}_{\varphi}^{H}(T_K) - \sigma_{o,2}^{K}(T_o)\right] + \sigma_{o,2}^{B}(T_o) + \bar{\sigma}_{\varphi 2}^{B}(T_B) \qquad /8/$$

Cracks on the surface will not appear if the resultant stress state $\sigma_{\varphi R}$ is smaller than the breaking strength of the tempered martensite:

$$\sigma_{\varphi R}(T_o) < \sigma^{B}_{zr}(T_o) \qquad /9/$$

Wherefrom we get the inequality determining the minimal thickness of the quenched layer δ :

$$\delta > b \left\{ 1 - \sqrt{\frac{\sigma^{B}_{o,2}(T_o) + \bar{\sigma}^{B}_{\varphi 2}(T_B) - \sigma^{B}_{zr}(T_o)}{\sigma^{K}_{o,2}(T_o) - \bar{\sigma}^{H}_{\varphi}(T_K)}} \right\} \qquad /1o/$$

For the applied steel Č.4732 an estimation of the value of the breaking strength in the quenched and tempered layer was made on the basis of the hardness profile. The strength of the quenched layer $\sigma^{K}_{zr}(T_o)$ and that of the tempered layer due to grinding $\sigma^{B}_{zr}(T_o)$ at the environmental temperature T_o are estimated to be the following:

$$\sigma^{K}_{zr}(T_o) = 2o5o \quad N/mm^2$$

$$\sigma^{B}_{zr}(T_o) = 14oo \quad N/mm^2$$

The plasticity limit at T_o for the quenched (martensite) layer is estimated to be approx. equal to the breaking strength.

$$\sigma^{K}_{o,2}(T_o) = \sigma^{K}_{zr}(T_o) \qquad /11/$$

And for the tempered part:

$$\sigma^{B}_{o,2}(T_o) = o,9 \ \sigma^{B}_{zr}(T_o) \qquad /12/$$

Owing to the lack of all the necessary data for the determination of thermal stresses from equations /2/ and /5/, the function of the plasticity limit of the quenched (martensite) and tempered steel due to grinding was estimated on the basis of experimental data for a similar type of steel in dependence of temperature in the range upto $T \leqq 500°C$.

In this temperature range the constant Young's module and Poisson's number are:

$$E = 2,1 \ . \ 1o^5 \quad N/mm^2$$

$$\nu = 1/3$$

The average linear thermal expansion coefficicnet in the region is

$$\alpha = 12. \ 1o^{-6} \ (1/°C)$$

For the quenched (martensite) part the plasticity limit is then:

$$\bar{\sigma}^{H}_{\varphi}(T) \approx \sigma^{K}_{o,2}(T) = a_K \ \bar{T} + \sigma^{K}_{o,2}(T_o) \qquad /13/$$

where $a_T = - 2,116 \ 6496 \quad N/mm^2 . °C$

and similarly for the tempered part due to grinding:

$$\bar{\sigma}^{B}_{\varphi 2}(T) \approx \sigma^{B}_{o,2}(T) = a_B \ \bar{T} + \sigma^{B}_{o,2}(T_o)$$

$$a_B = - 1,39522 \quad N/mm^2 \ . \ °C \qquad /14/$$

$$\bar{T} = T - T_o$$

The temperature during quenching T_K and during grinding T_B at which the stress state due to cooling passes into the region where Hook's rheological model holds, are calculated using the expressions /13/ and /14/:

$$T_K = \frac{\sigma^{K}_{o,2}(T_o)}{\frac{\sqrt{3}\,\alpha E}{2(1-\nu)} - a_K} = 380°C \qquad /15/$$

$$T_B = \frac{\sigma^{B}_{o,2}(T_o)}{\frac{\sqrt{3}\,\alpha E}{2(1-\nu)} \left(\frac{a}{b}\right)^2 - a_B} = 293°C \qquad /16/$$

The plasticity limits for the quenched (martensite) and tempered part of steel due to grinding at temperatures T_K and T_B are as follows:

$$\sigma^{K}_{o,2}(T_K) = 1245 \quad N/mm^2 = \bar{\sigma}^{H}_{\varphi}(T_K) \qquad /17/$$

$$\sigma^{B}_{o,2}(T_B) = 850 \quad N/mm^2 = \bar{\sigma}^{B}_{\varphi 2}(T_B)$$

The minimal required thickness of the quenched layer from inequality /1o/ and /17/ is $\delta > 3,o4$ mm.

In the case that during the grinding process there comes to no remarkable tempering of steel the inequality /1o/ has no real solutions. This means that in this case no cracks appear on the ground surface.

5. CONCLUSION

On the surface of pin bearings of engine crankshafts the phenomenon of grinding cracks frequently appears during the grinding process. In the forging process of the billet the steel flows in the die so that the steel from the billet centre comes to the surface at places of pin bearings. In this part of the billet the steel is of under-average quality, which was one of the main reasons for the suppositions that the steel quality is responsible for crack initiation.

Our investigation was carried out on crank-pin bearings of standard production and segments of bars forged from high and low quality billets of CrMo steel. The sample bars were heat treated in the same way as the crankshafts, whereas the requirements of grinding conditions were raised up to 6-times.

On none of the ground segments any cracks appeared, but on the contrary cracks were found on the crankshafts manufactured from high quality steel.

On the basis of these findings the supposition that steel quality could be the cause of crack initiation in the present conditions of surface quenching and grinding was eliminated. Strict selection of materials, which is urgent for forging and structural strength of the crankshaft, is satisfactory also for high quality surface quenching and grinding. Thus the problem of grinding cracks reduces only to the conditions of surface quenching and grinding.

By an analytical model an estimation of the magnitude of stresses after surface quenching and grinding was made. The model also tries to establish the relation between the depth of quenching and resistance to the initiation of grinding cracks.

On the ground surface cracks were found only on those pin bearings where due to intensive over-heating of steel during the grinding process the hardness at the surface was drastically reduced. In these cases a tempered martensite appeared in the narrow zone with the thickness of δ_1 = 150 ... 200 µm. The thickness of the quenched surface in all the cases of cracked pin bearings was approx. 2mm and always less than 3 mm.

The experimental findings are in agreement with the results obtained by the calculation model.

6. REFERENCES

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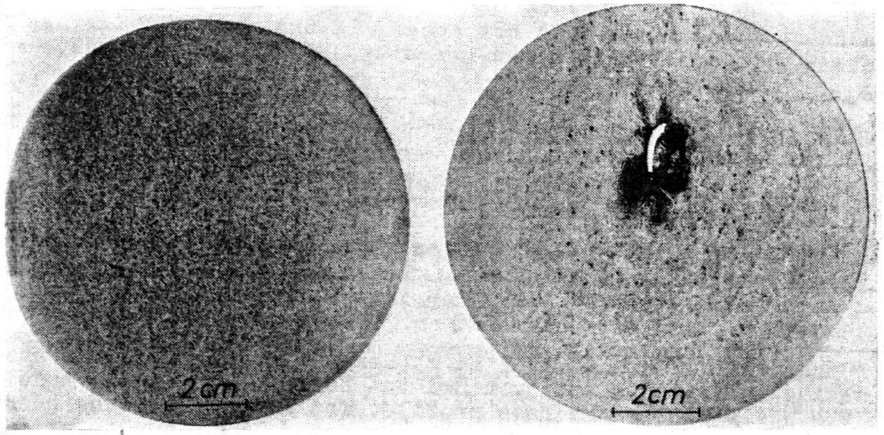

Fig.1-2 Macroscopically etched cross section of a segment forged from high quality billet (left) and low quality billet (right)

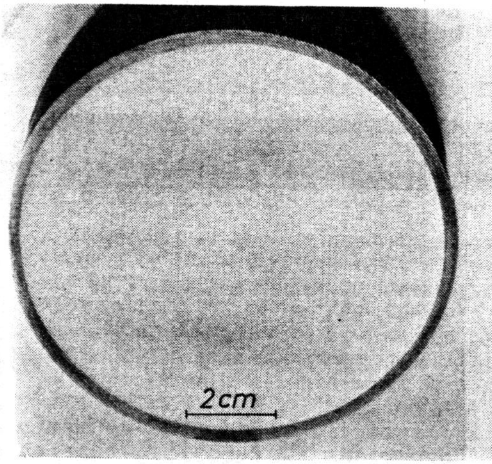

Fig.3 Cross section of segment with quenched surface

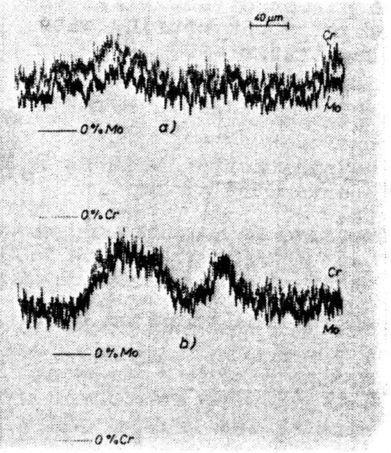

Fig.4 Cr and Mo distribution in steel a) on the surface b) in the billet centre

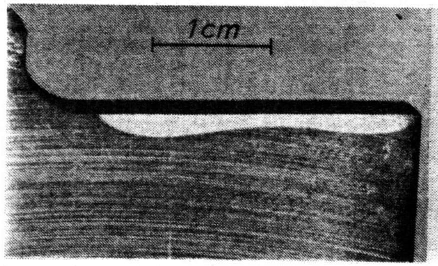

Fig.5 Geometry of the quenched surface on the acial cross section of a pin bearing with cracks

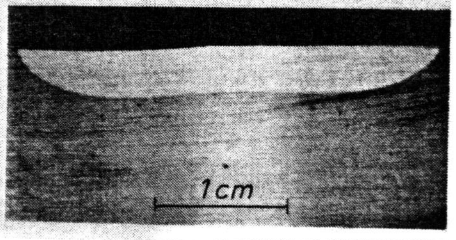

Fig.6 Geometry of the quenched surface on the axial cross section of a segment

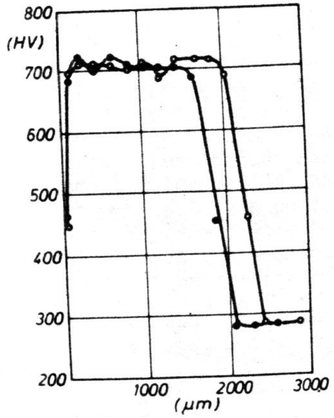

Fig.7 Hardness profile measured on two places of the axial cross section of a pin bearing with grinding cracks

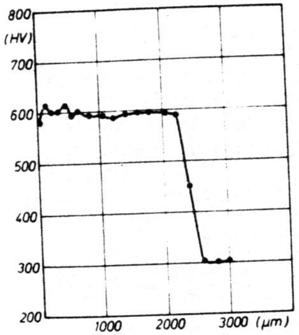

Fig.8 Hardness profile on the axial cross section of a pin bearing without cracks

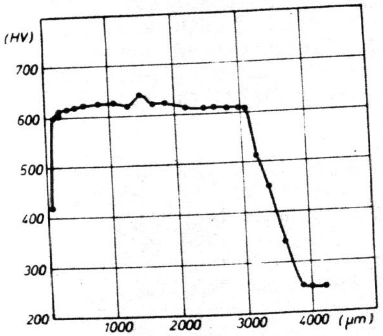

Fig.9 Hardness profile on the axial cross section of a segment without cracks

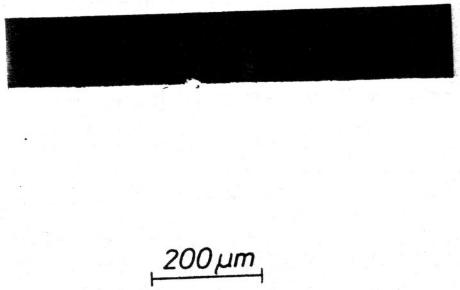

Fig.lo Two intergranual cracks in the quenched surface of a pin bearing: magn. loo x

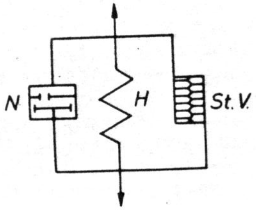

Fig.11 Rheological model