THE FAILURE AND REPAIR OF A 300 MN PERCUSSION PRESS SLIDE BLOCK

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INTRODUCTION

After nearly one year service life of a 300 MN Percussion Press cracks appeared at the outer surface of the slide block ejecting oil with high velocity. After dismantling the press starting cracks could be observed on the surface of the fillet in form of a smooth notch near that region of the slide block where the load is transmitted by a bronze breast plate see Fig. 1. The main crack took its course along one third of the inner circumference (about 1200 mm long) at different levels in the contour of the fillet. This happened obviously due to more than one crack starter area. At the opposite side of the main crack some smaller cracks of a length about some mm to 20 mm were also detected in the fillet. At time of observation these cracks did not yet grow together.

The life time of the press was prognosticated for $4{,}2 \cdot 10^6$ impacts of forging at different loads in a given loading collective. This should correspond to a working time of ten years.

The failure of the press occurred after about 80000 impacts of the pretended loading collective. This is only about 1/50 of the expected life time.

FAILURE ANALYSES

Metallographic failure analysis

The cracked slide block of about 100 to weight showed in a metallographic investigation the typical Ferrite-Perlite structure, frequently in Widmannstätten patterns. The quantity, the size (found by inspection till to a diameter of 4 mm) and the distribution of the casting pores are in this big steel casting not extraordinary. There was nothing unusual in the structure, also in the crack areas.

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From the knocked out cracked notch zone, specimens for determination of the strength and fatigue properties were prepared. The yield strength $R_{po,2}$= 283 MPa, the tensile strength R_m= 510 MPa, elongation A_5= 20 %, area of reduction Z= 35 % (all values in average) were not much impaired compared with those values of cast-on test bars determined in the production of the slide block ($R_{po,2}$= 288 MPa, R_m= 530 MPa, A_5= 26 %, Z= 34 %). For this little deterioration of the values the greater porosity of the big steel-casting is responsible.

Much more affected by the porosity are the fatigue properties. The fatigue limit did not exceed $\Delta\sigma(R= -1)= \pm 150$ MPa compared with $\Delta\sigma(R= -1)= \pm 250$ MPa of specimens of the cast-on test bars. It should be taken into consideration too that a further reduced fatigue strength exists by the higher probability of larger porosity in the big volume of the steel casting compared to specimens.

All cracks - carefully opened by slitting the knocked out material from the opposite side of the cracks and striking off in liquid N_2 - had their origin in casting pores as to be seen in Fig. 2. The fracture surface revealed the typical arrest lines of a fatigue fracture surface in a half circular manner (half penny shaped crack).

An analysis of the fracture surface in the Scanning Electron Microscope (SEM) revealed sometimes fatigue striations of different spacings. Most of the areas were flattened by rubbing of the two fracture surfaces especially at the border zones against the grinded fillet. Fig. 3 is a view of the grinded notch surface with squeezed out lips marking a beaded edge out of the notch surface (arrows). This indicates there a high pressure in the crack surface during the course of alternating loading in service of the percussion press. Asperities of the crack surface became even (Fig. 4). As to be seen further in Fig. 4 in depression areas fatigue striations are well developed and permits a rough estimation of the crack growth rate. Near the fillet surface (neighbourhood of the casting pores) the crack growth rate corresponds to 2 - 3 μm/cycle. 20 mm beneath the surface the local growth rate amounts already 7 - 9 μm/cycle.

It took at least about 6000 cycles for the crack to run to a distance of 20 mm (additionally to the number of necessary cycles for crack formation). Exceeding this distance, macroscopically no arrest lines are visible and in the SEM no fatigue striations could be detected indicating then a fast crack growth rate. At least the crack arrived the outher surface of the slide block after 81000 impacts of forging, due to a distance of the running crack of about 500 mm.

The arresting marks in Fig. 2 show further that the crack progress normal to the fillet into the wall of the slide block is quite faster than at the surface.

After a crack growth of some individual half penny-shaped small cracks to a depth of 20 - 30 mm they joint together to a common crack front passing through the whole steel casting in a very fast crack propagation rate with nearly no crack propagation components normal to the main direction.

Stress analysis

The main attention was paid on the fillet as the crack starter area. The stresses were calculated by a nonlinear finite element programm which allows a very exact modeling of the fillet contour.
The calculations are based on the dimensions of Fig. 1 and took in consideration an axisymmetrical structure under an axisymmetrical load. No friction between the breast plate and the slide block is assumed. Between the lateral wall of the slide block and the breast block exists a crescent gap of max. 0,25 mm.
According to the oil film an approximately constant oil pressure acts on the surface of the breast plate and on the fillet. An elastoplastic behaviour of the steel casting is assumed and the material dates found by our tests were used. The bronze breast plate showed only elastical behaviour.
It is very important to take the upper plate (350 mm wall thickness) and the lateral bracing plate (160 mm) into consideration (Fig. 1). In the analysis of the structure only a parallel movement in the direction of the vertical axis of the upper horizontal boundary surface of the slide block was accepted. The stiffness of the construction caused an impediment of the elastic deformation in the fillet region and a high stress level obviously exceeding the yield stress of the steel casting at the fillet.
The results of the analysis revealed the highest stress component being tangential to the fillet surface. The stress component normal to the contour surface is the oil pressure. The third stress component is operating in circumferential direction and is a tensile stress with an essentially lower value.
In Fig. 5 the tangential distribution of the main normal stress along the internal radius of the fillet is plotted.
Fig. 6 shows the distribution of the main normal stress in direction normal to the fillet contour for impacts of 300, 200 and 100 MN interpolated graphically over some elements and extrapolated to the surface. At the first loading plastic zones arose with peak stresses especially at the outer contour of the contact surface between breast plate and slide block developing an elastic residual stress state after unloading. At further loads beyond the max load the system will behave elastically (shake down).
The experimental statement of highly pressed and deformed lips could be confirmed by the calculated result which showed a high residual pressure component in the fillet of 200 MPa.

Analysis of Damage

In order to assess the damage by a loading collective a constant equivalent damaging stress amplitude $\Delta\sigma_e$ was introduced [1].
Depending on different loading collectives and the slope factors m of the Wöhler curve, the eqivalent damaging stress amplitude will be 97 % - 87 % of the stress amplitude due to the maximum impact load of 300 MN.
The stress amplitude is then $\sigma_a{}^e$= 196 MPa respectively with the safety factor of γ_s= 1,25 $\sigma_a{}^e$= 245 MPa.
Related to the experimental Wöhler curve this stress amplitude corresponds to 10^5 cycles. This is far from the required number of stress reversals of $4{,}2\cdot10^6$. There is a good qualitative aggreement with the fact that the slide block failed after 81000 impacts.
The reason for the failure is clearly the high stress niveau. Some effects for decreasing the life time should further be taken into consideration:

* The higher stress concentration factor is larger than 2 (the stress concentration for a sphere) at the often irregular shaped pores.
* The additional oil pressure between the lateral contour of the breast plate and the lateral surface of the slide block could be assessed about 500 bar at the 200 MN load. This pressure opened cracks, and oil was injected into the crack by high pressure.
  This is in accordance with the observation that small bronze particles could be detected at the fracture surface (originating from the breast plate).

Fracture Mechanics Estimation of the Crack Growth

In this detailed stress analysis the fillet area is represented by an elastic half space. As to be seen in Fig. 6 an approximately linear stress distribution exists over a distance of 15 mm into the interiour of the slide block.
For a half-penny shaped crack at the surface the ΔK (stress intensity factor range) can be calculated. A variation of the geometry factor Y with respect to the linear stress distribution between 0,44 to 0,77 is taken into consideration [3]. Under the assumption of a half-penny shaped crack with a radius of 1 mm (larger pores with diameter of about 4 mm could be detected) a ΔK value of 446 $N/mm^{3/2}$ can be determined. This is far above the threshold value ΔK_{th}= 228 $N/mm^{3/2}$ estimated from da/dN-ΔK curves of specimens prepared out of the slide block material. This starting crack is therefore able for crack growth. The essential increase of the stress intensity factor corresponds with the increasing crack growth rate observed by inspection.

For an estimation of the number of loading cycles to failure Y was assumed to be constant. The parameters of the Paris Law $C = 0{,}57 \cdot 10^{-16}$ and $m = 4{,}5$ are taken from the mentioned $da/dN - \Delta K$ curves. The integration of the Paris Law results in $N = 0{,}31 \cdot 10^5$ cycles for max. Y and $N = 2{,}31 \cdot 10^5$ cycles for min. Y. The mean value lies in the order of magnitude of the actual number of cycles to failure.

REPAIR OF THE SLIDE BLOCK

All the stated crack zones were carved out. The slots were filled with a special welding material in a special welding process. After each welding deposit a nondestructuve testing with a magnetoscopic method was performed and flaws and pores not greater than 0,5 mm were allowed.

The upper layers work as buffer zones, where the new contour of the fillet was carved out. There no flaws and pores greater than 0,2 - 0,3 mm could be detected after grinding and polishing in the fillet surface.

The material of the welded slit volume has to some extent superiour mechanical properties than the steel casting. The assumed fatigue strength amplitude for $4{,}2 \cdot 10^6$ cycles lies at $\sigma_a(R= -1) = 262\text{–}272$ MPa and $\sigma_a(R= 0{,}1) = 140\text{–}147$ MPa.

In crack propagation tests a threshold could be estimated by $\Delta K_{th} = 240\ N/mm^{-3/2}$ [2].

As to be seen in Fig. 7 it was suggested to increase the radius of the fillet. The calculated main stress range at the mainload 300 MN is now only $\Delta\sigma_I \approx 400$ MPa compared with the original construction $\Delta\sigma_I \approx 500$ MPa.

The equivalent damaging stress amplitude with the same safety factor will be $\sigma_a{}^e = 215$ MPa. A look at the Smith diagramm, Fig. 8 (which was drawn on the basis of experimental data for the endurance limit of $4{,}2 \cdot 10^6$ cycles for the welding material) reveals that the calculated stress state lies somewhere in the hatched area which indicates an experimental uncertainty region due to the assumed scatter of the fatigue tests (only a limited number of specimens were available). Simulation fatigue tests according to the loading collective with specimens out of the welding material did not show any cracks. But it should be born in mind that under this special favourable welding conditions for preparing this specimens the failure density is lower and welding stresses are negligible.

Decesive is the influence of the mean stress. There are certainly some internal stresses resulting from the welding process which can not easely be determined. To get compressive stresses near the surface a shot peening of the fillet surface and polishing treatment were suggested. These resultant residual stresses can hardly be calculated accurately too. Experimental determination of the residual stresses is not easy in this case and can often be uncertain.

In Fig. 8 two examples are plotted in the Smith diagram. The greatest calculated possible stress range for 300 MN impact forging cannot always endure $4{,}2\cdot10^6$ cycles. (This is not necessary because due to the intended loading collectives only $5\cdot10^5$ cycles of 300 MN are planed).

Yielding a compressive stress of 155 MPa at the surface the construction will sustain the maximum load of 310 MN (highest possible load) over the 10 years service life calculated for the most severe loading (see Fig. 8 I).

If it is possible to yield a compressive stress of only 50 MPa (e.g. shot peening) the equivalent stress range $\Delta\sigma_e$ will be transfered in the safety region (see Fig. 8 II). The residual stress state of the fillet surface is cleary relevant for the intended life time of the slide block.

It cannot be excluded that flaws and pores with a size about 0,5 mm are situated close under the surface (they are there hardly detectable). A fracture mechanical assessment showed for a penny-shaped crack of 0,5 mm diameter situated 0,05 mm under the surface a ΔK value of 237 $N/mm^{3/2}$ [4]. This lies in the order of magnitude of the threshold with ΔK_{th}= 267 N/mm^2. Ignoring ΔK_{th} it could be estimated that after 43000 cycles the crack gets through the surface. At this stage the ΔK value is difficult to estimate.

Applying then a half-penny shaped crack of r= 0,6 mm the crack would reach a critical size after 112000 cycles. This is less then the demanded number of cycles.

The way to make the slide block safe against cracking can be done by a decrease of stress ratio R and a minimizing of the failure size in or near the surface of the fillet.

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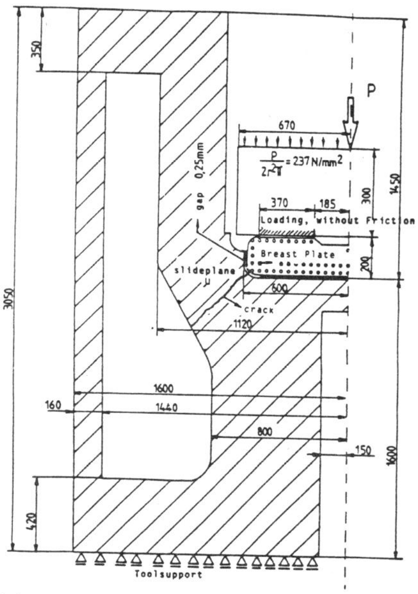

Fig. 1 Percussion Press Slide Block

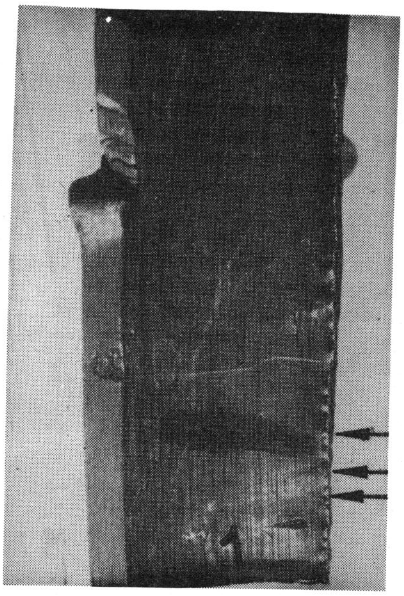

Fig. 3 Grinded Fillet Surface (Arrows deformed Crack edge)

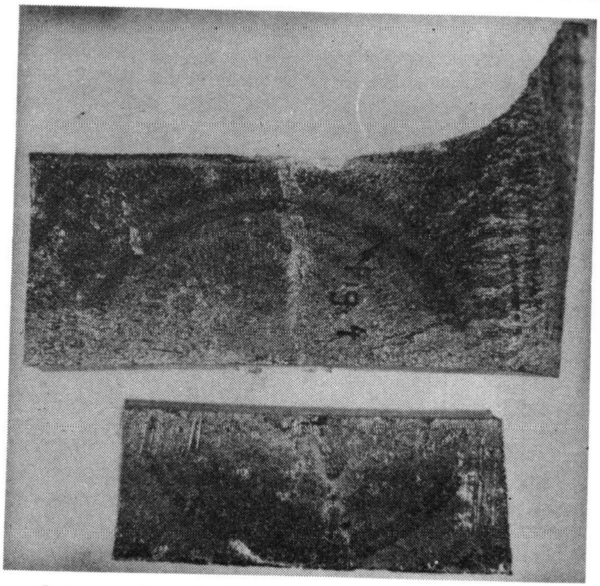

Fig. 2 Macrofotographs of the Crack Surface of the Main Crack (Pores and Arrest lines)

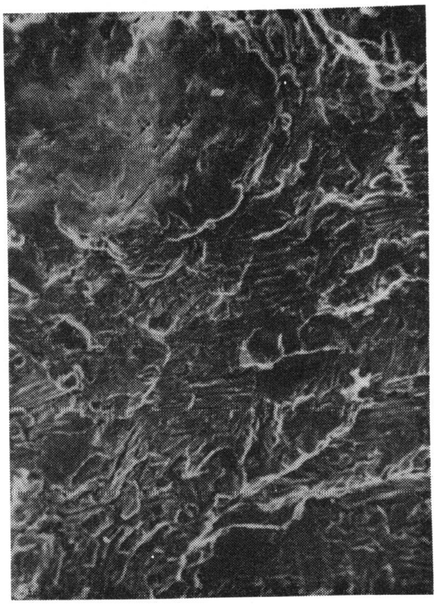

Fig. 4 Fracture Surface SEM (Location see Fig. 2)

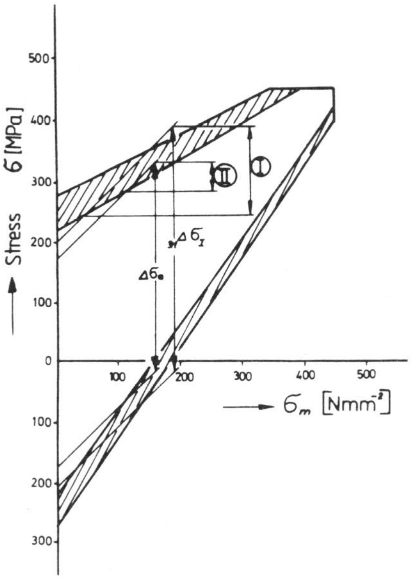

Fig. 8 Smith Diagramm for $4{,}2\cdot10^6$ Cycles (Examples)

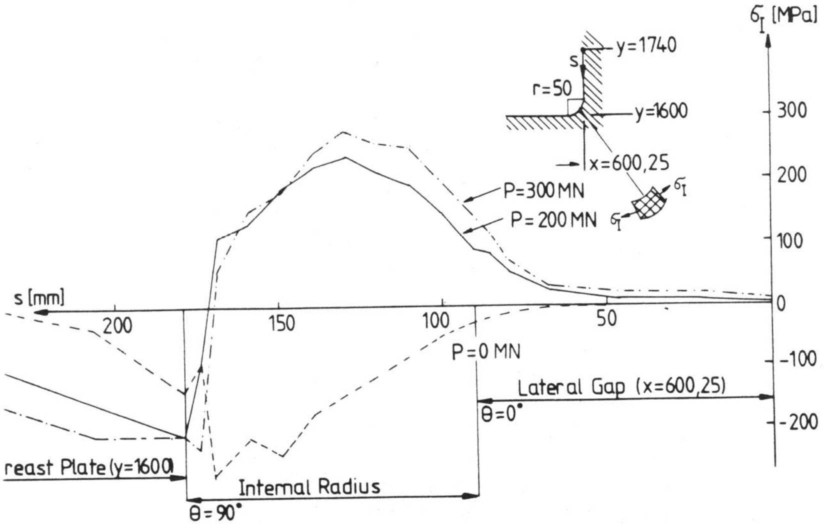

Fig. 5 Tantential Main Normal Stress along the Internal Radius of the Fillet

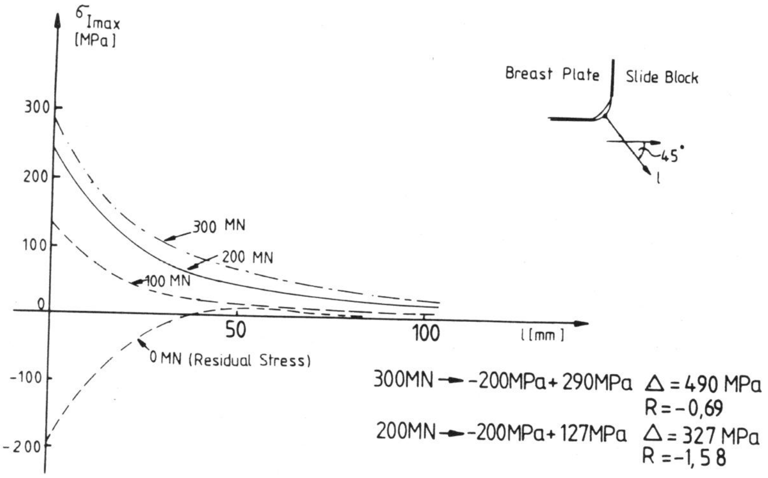

Fig. 6 Stress normal to the Fillet Surface

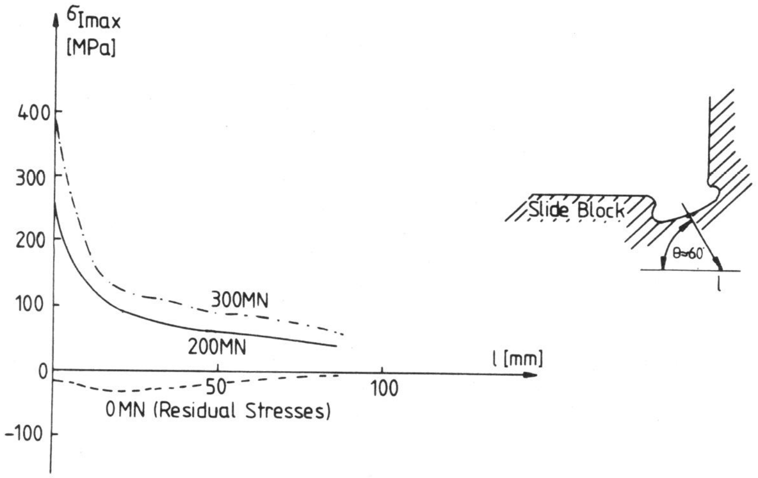

Fig. 7 Stress normal to the Fillet Surface after modified Fillet Contour