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Failure analysis of the rod of a hydraulic cylinder

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Abstract

This paper presents the failure analysis of the rod of an oleo-hydraulic cylinder of a machine for fatigue testing large diameter heavy duty cables for marine applications. A distinct feature of this machine is its size: the 3990 mm long rod has an outside diameter of 340 mm. The rod is manufactured machining a solid cylinder of 42CrMo4 steel, along most of its length, into an hollow cylindrical rod with inside diameter 165 mm. Typical maximum loads applied are of the order of 10000 kN. In one of the extremities where load is applied, the rod is solid (not hollow), and the complete fracture occurred in the transition of the solid to the hollow parts, during a test performed under maximum load of 8200 kN under *R* (load ratio) of approximately 0.
The fracture is flat and perpendicular to the rod axis, *ie* to the load direction, revealing a smooth surface appearance. Fracture surface roughness increases from the inner to the outer radius. Close to the outer radius evidence of ring-like beach marks was found. The fracture was due to fatigue cracking initiated at the fillet radius of the transition solid/hollow rod, and propagated until complete, sudden fracture.
The paper discusses this case in the light of (i) a conventional Soderberg approach, and (ii) a DIN 743 analysis. Lessons learned in the case, particularly as concerns a comparison of the typical Soderberg approach and the DIN 743 procedure, are presented.

Keywords: Fracture; fatigue; case study; DIN 743; shaft design; Soderberg approach;

1. Introduction

The piston rod of a hydraulic cylinder of a testing machine, used for fatigue and tensile testing of cables, suffered sudden complete rupture while the machine was performing a fatigue test. The rod cylinder was machined internally,

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producing a hollow cylinder along most of its length. A distinct feature of this machine is its size: the 3990 mm long rod has an outside diameter of 340 mm. The rod is manufactured machining a solid cylinder of 42CrMo4 steel, along most of its length, into an hollow cylindrical rod with inside diameter 165 mm. Typical maximum loads applied are of the order of 10000 kN. In one of the extremities where load is applied, the rod is solid (not hollow), and the complete fracture occurred in the transition of the solid to the hollow parts, during a test performed under maximum load of 8200 kN under *R* (load ratio) of approximately 0.The fracture occurred in the shoulder fillet in the end of the hollow part of the rod. Figure 1 shows the fracture surface. The fracture surface reveals different mechanisms of cracking. The dominant type of fracture surface is of smooth appearance, resulting from fatigue, constituting a ring around the machined internal hollow region of the rod. Concentric lines, beach marks or striations typical of fatigue fractures, are identified in the periphery of this smooth ring surface, Figure 2, which also displays the final fracture region; a detail of a plane stress fracture (inverted cone) appearance at the shaft surface is evident. The surface quality resulting from the machining operation can be considered rough, with deep grooves, as can be seen in Figure 3.

Rod material testing consisted of tensile, hardness and Charpy testing, and microstructure and metallographic characterization. The failure analysis carried out involved the finite element modelling of the component, since it was realized that the shoulder fillet radius, in the transition from hollow to full cylinder, could be the origin of the inadequate fatigue strength of the rod.

Figure 1 – Fracture surface.

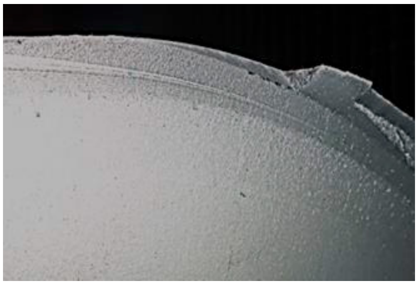

Figure 2 – Detail of the outer part of the fracture surface, showing the dominant fatigue region (smooth surface).

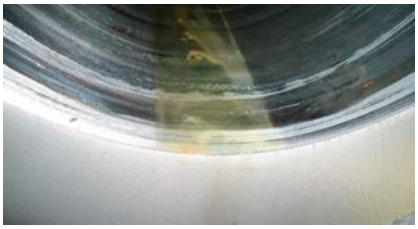

Figure 3 – Fatigue surface, and appearance of the machined interior surface of the rod. (the photograph shows some oil still present in the rod when the photo was taken).

2. Finite element analysis of the stress concentration factor in the rod

In order to determine the stress concentration factor of the shoulder fillet of a rod, a finite element model was built using ABAQUS software. The radii at the shoulder fillet considered for this study were: 1 mm, 2 mm, 3 mm and 15 mm. Axisymmetric elements were employed, with quadratic formulation and reduced integration (ABAQUS element reference: CAX8R). As an example, the geometry and the boundary conditions applied for the model with a radius of 3 mm are presented in Figure 4. Several mesh element sizes were evaluated in order to determine the effective stress concentration factor. For the finest mesh, the results of *yy* stress are presented in Figures 5, 6 and 7. The element face size for this case is visible in Figure 7, corresponding to a face width of 0.05 mm.

The evolution of the concentration factor for the different radii is presented in Figure 8. The minimum element face size for an accurate stress concentration factor determination depends on the radius considered. However, after this study, it is concluded that using quadratic elements, the element face width should be 10 times less than the radius.

Considering the different models built, a calibration of the stress concentration factor was obtained, Figure 9. As expected, this factor increases when the radius decreases; the increase is particularly important for low values of radius, compromising the integrity of the rod piston. The maximum in-plane stress is also obtained from the finite element models; for the case of a radius of 1 mm, its direction is shown in Figure 10. Looking to the direction of maximum stress, the ledge on the fracture surface is in accordance with this direction.