Fatigue Fractures as Reason for Failure of Pressure Vessels Operating under Cyclic Loads

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Failures which recently occurred on pressure vessels give reason for the assumption that they were caused by fatigue fractures which were due to an underestimation of the influence of cyclic loads. Such failures were observed on vessels operating at room and elevated temperatures.

Figure 1 shows such a failure. In this case a sphere with an inside diameter of 1336 mm and a wall thickness of 44 mm was involved. The vessel was made from material St E 51 and used as water bottle in a large forging plant. As the figure shows, parts of the burst vessel were removed for material testing. Therefore, the total extent of the failure does not appear.

The pressure vessel failed as a result of a fatigue crack which occurred in a properly back-welded and ground smooth nozzle weld (Figure 2). No indications of welding defects were found. Therefore, the conclusion can be drawn, that the fatigue crack has to be attributed to unallowable overstressing.

Figure 3 shows part of a pressure reading diagram taken prior to the failure during a forging operation, from which the pressure fluctuation in the hydraulic piping system close to the quick operating valve becomes obvious. When neglecting the highest pressure peaks of the diagram it can be assumed that this curve reflects the fluctuation of pressure in the sphere. From the curve it becomes obvious, that the pressure ranged between 100 and 273 bar which is equal to a double-amplitude of 173 bar or 66,7% of the design pressure. The frequency applied was approx. 5 cycles/sec.

Except for the design pressure, no further data were given by the purchaser. The sphere was designed according to AD-Merkblatt B1 for non-cyclic service. In accordance with this AD-Merkblatt, cyclic loads (double-amplitude) of -10% of the design pressure are allowable. Considering these facts the failure of the pressure vessel is not surprising.

In many cases lack of knowledge of the loads actually to be expected is the main reason for the frequent occurrences of such failures. This lack of knowledge results from an erroneous estimation of the practical behaviour of pressure vessels in operation as well as the development of loads, which were not expected and could not easily be foreseen. When installing pressure vessels in a pipe-line system as for instance in forging plants, resonances might occur which result in an unwanted increase of the pressure amplitude. By changing the geometry of the pipe-line system such influences can effectively be prevented. Until a few years ago cyclic loads to be expected in operation were not or only insufficiently considered in the design of pressure vessels. The first indications with regard to selection of material and geometry of pressure vessels subject to pulsating loads were given in BASF-internal regulations in 1940. 1967 a VdTÜV-Merkblatt for the design of boiler drums was issued, which included regulations considering cyclic loads in the region of low-cycle fatigue. Nowadays efforts are made by various authorities to establish basic rules*) for the design of pressure vessels operating under pulsating loads. For this purpose profound knowledge of the stresses to be expected and the specified lifetime as well as the material behaviour and the geometry at pulsating loads are of interest.

A pressure vessel with various nozzles will serve as an

example to demonstrate of which kind the loads are, that may become critical for a vessel (Figure 4).

The stresses in the vessel wall and in the area of the longitudinal and circumferential seams increase proportionally to the inside pressure of the vessel. As the design includes a safety factor providing a sufficient margin against plastic deformation, the stresses in the vessel wall are safely within the elastic region of the material. In the area of undercuts and defects in the welding seam, however, plastic deformation might occur. If the behaviour of such weld connections at cyclic loads shall be investigated, stress-controlled fatigue-testing devices have to be used.

A completely different situation will be found in the area of local discontinuances such as nozzles, attachments,etc. Due to the considerable effect of notches in these areas a plastic deformation occurs, which goes together with a reduction of peak stress. In consequence of the cyclic deformation of the vessel these areas are subject to an alternating strain, which is determinant for the material behaviour. Accordingly, only strain-controlled laboratory tests will furnish adequate information. By this test the specimen will be exposed at each load cycle to a fluctuating strain.

The result of such a strain-controlled fatigue test illustrated by the hysteresis loops recorded is shown on Figure 5. During this test a strain of 16 ± 4^{o}/oo was applied. The first cycle with a strain of 20^{o}/oo (16+4) entered far into the plastic region and at the amplitude of ± 4^{o}/oo a considerable hysteresis occurred. Forces and stresses entered partially into the compression region. Changes in the material structure and the development of micro cracks could be easily traced by means of the records. After 1754 strain cycles the specimen failed completely.

The tests were made by using rectangular specimens from

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*) Revised edition of TRD 301, revised edition of DIN 2413 ASME Code, Sections III and VIII, Division 2

material St E 51. Unwelded and unmachined specimens were used for determining the number of strain cycles which produce failure of the base material. The butt-welded specimens were tested with weld surfaces in as-welded condition as well as after the seam had been ground flush.

Figure 6 shows the shape of the specimen chosen, a microsection and the view of a fracture surface.

On the fracture surface several fatigue cracks spread over the cross section are to be found, which result from small weld defects (pores, inclusions) inside the material which cannot be detected on the x-ray films. While the fatigue cracks are located at an angle of 90° to the loads applied, the fracture residual appears as shear fracture located at an angle of 45° to the axis of the specimen. All welded specimens, regardless of whether the surface has been ground or not, are within this line.

Figures 7 and 8 give the number of stress cycles which produce failures dependent on the strain respectively stress amplitudes. It is obvious that the number of strain cycles to failure applied during the strain-controlled fatigue tests is considerably lower on the welded specimens than on the unwelded ones. For stress-controlled fatigue tests such distinction cannot be made. A very small modification of the stresses might result in a considerable increase of strain. Therefore, stress-controlled low-cycle fatigue tests are unusual. In addition it has been found, that unmachined and ground welding seams give the same results. The reason for this behaviour results from the fact that the fracture starts inside the specimen. This means that with loads in the plastic region as these, the grinding of the welding seam is of no advantage with regard to the lifetime.

It has been found, that the specimens can stand a large number of stress-cycles despite the extreme loads. This means that the exact knowledge of the operating loads to be expected and the specified lifetime allows for a safe design in the field of low-cycle fatigue, provided the fatigue strength for finite life of the materials to be used is available.

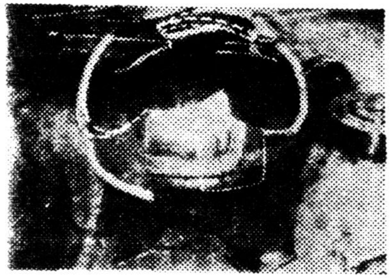

Fig. 1

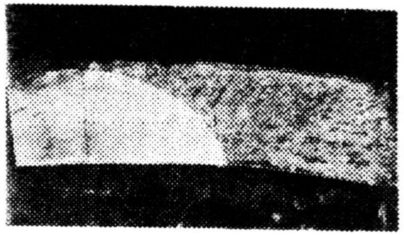

Fig. 2

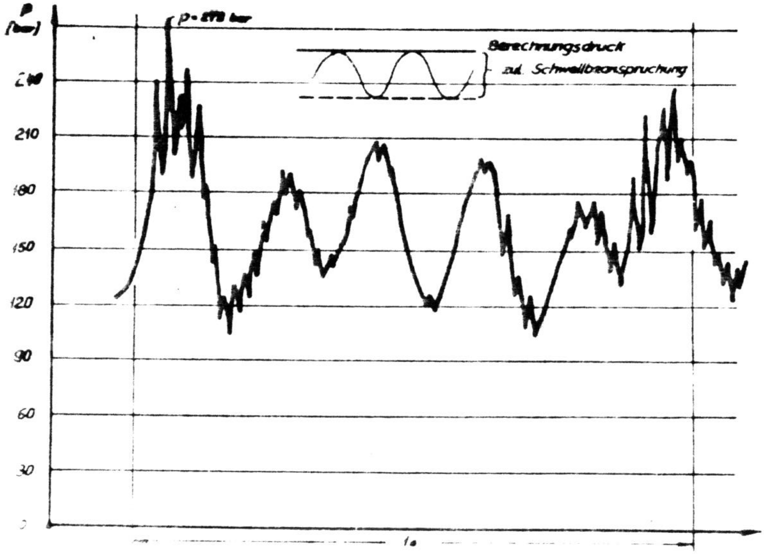

Fig. 3

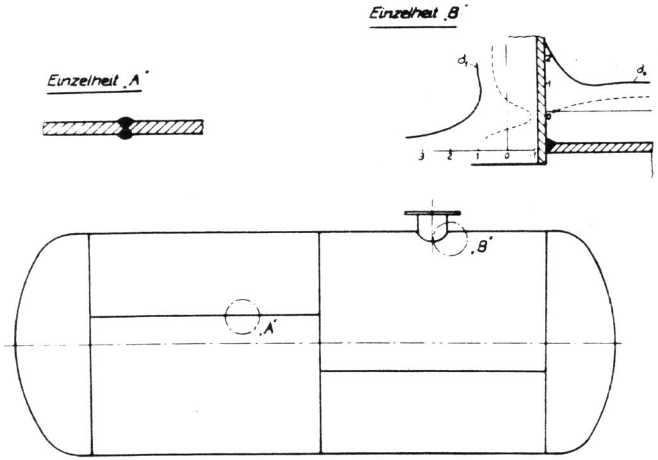

Fig. 4

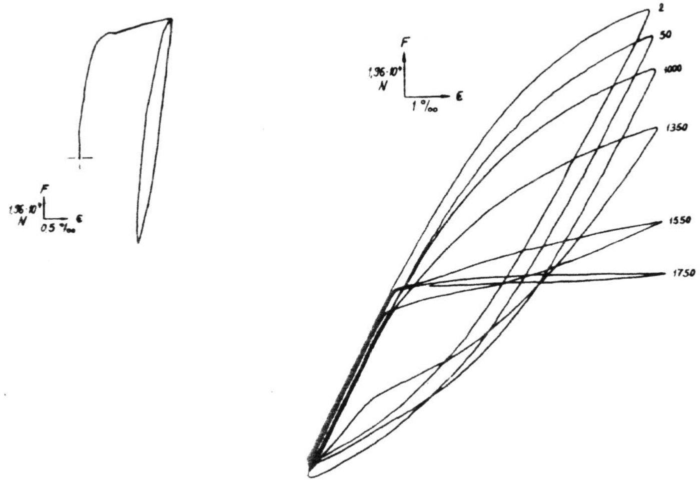

Fig. 5

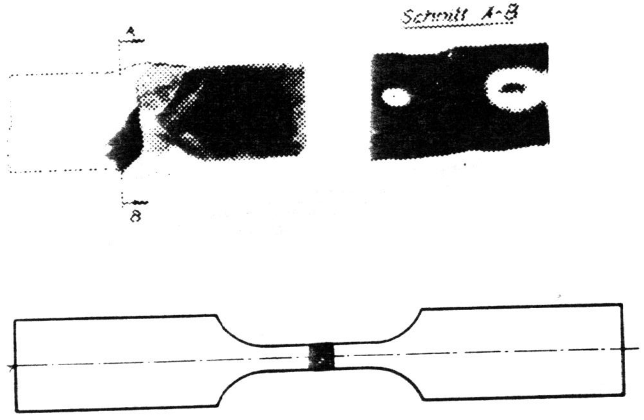

Fig. 6

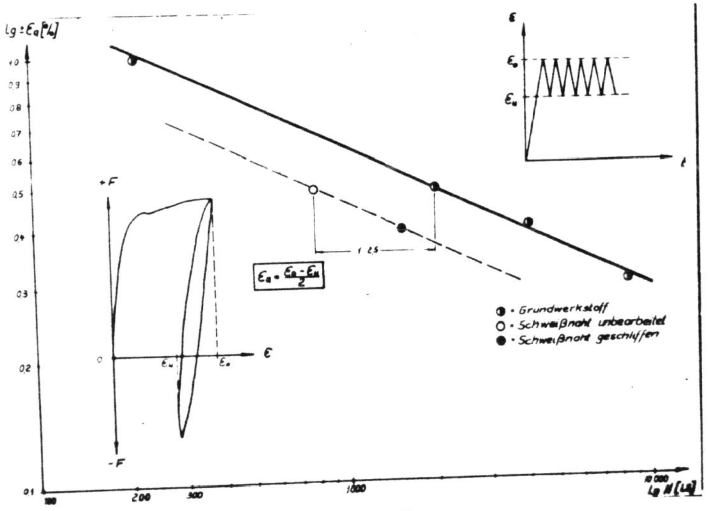

Fig. 7

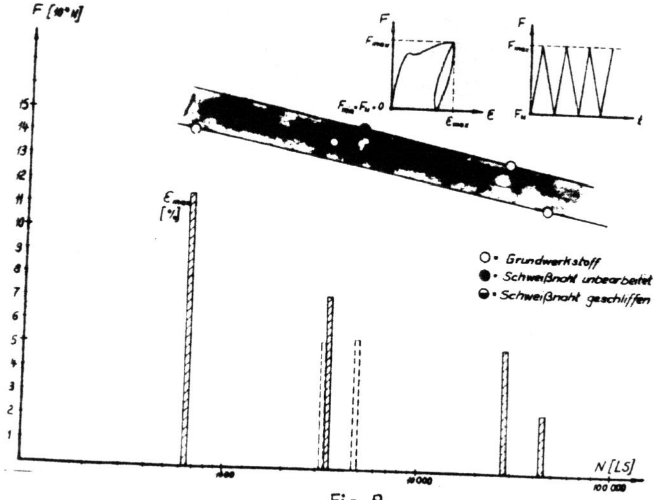
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Fig. 8