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Studies of Faults in Used Valves, a Case Studies

R. Dusil

STUDIES OF FAULTS IN USED VALVES. CASE STUDIES

Robert Dusil
Steel Research Center, Uddeholms Aktiebolag, Sweden

1 SUMMARY

A fractographic investigation of compressor valve reeds which have failed in service was carried out using a scanning electron microscope in an effort to establish the cause of the failure. Some of the conclusions drawn from these studies can be formulated as follows:

Fatigue fractures account for a large proportion early failures of valves in compressors. The fatigue cracks start at defects which originated during the manufacture of the strip steel or the fabrication of the valve components.

Defects originating from valve fabrication out of strip steel are considered to be the most serious and the most common. Such defects include blanking marks, burrs and edge cracks. Transverse scratches, rolling defects and corrosion pits are other examples of starting points for fatigue fracture. All of these defects occur on the surface, where the damaging effect of the notch is the greatest.

Crack starters of metallurgical origin were hard oxide inclusions. However, compared to other defects, crack-initiating inclusions are rare.

Fractographic analysis indicated that some failures are caused by overloading of the valve reed above the seat. It would appear that the mechanical limitations of the material are primarily associated with the conditions which prevail above the valve seat.

Cold rolled strip steel which is used for valve manufacture is a very high-strength material with an ultimate tensile strength of about 1800 - 2100 MN/m^2 (260 - 300 ksi). The material is relatively notch-sensitive. The phenomena associated with crack initiation may be regarded as critical from the viewpoint of valve failure, while subsequent stable and unstable crack growth is of secondary importance. An effective removal of the most dangerous defects will prolong the service life of the valve component.

R. Dusil is Manager, Mechanical Properties, Steel Research Center, Uddeholms Aktiebolag, S-683 01 Hagfors, Sweden

2 INTRODUCTION

Modern technology places ever-increasing demands on the strength of design materials, especially in dynamically stressed machine components which are subjected to a relatively large number of repeated loads. The faultless function of these machine components is often a prerequisite for the faultless function of the entire machine.

Valve reeds in air or refrigerant compressors may be regarded as one of the most dynamically stressed machine components. The trend in compressor design is towards smaller compressor size without loss of capacity. The reduction in size is compensated for by increased speed. The demand on reliable valve function is further accentuated by the fact that the loading geometry of valves is becoming increasingly complicated and the nominal stress in the reed is steadily rising. Experience shows that valve failures are caused mainly by fatigue fracture. This paper reports some fractographic studies of fractured valves. The cause of failure has been analysed in relation to the external and internal nature and condition of the valve. Because of the complexity of the failures it is impossible to make any general conclusions.

The investigations were carried out on valves made of steel containing 1 % C and AISI 420 stainless steel containing 0.35 % C, 1 % Mo, 13 % Cr. The valves material was produced by different strip steel manufactures and by different processing.

3 STRESSES IN VALVE REEDS

A flapper valve (also known as a reed valve or a leaf valve) operates both as a seal and as a spring. The mode of operation of a flapper valve is illustrated schematically in Fig. 1 (1).

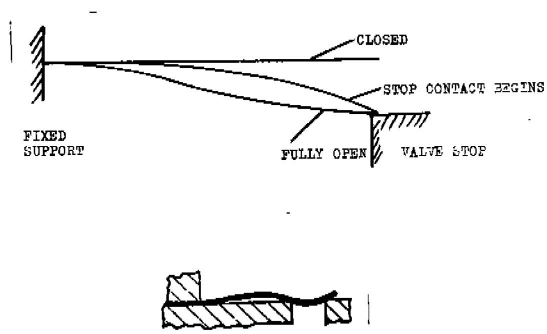

Fig. 1 Schematic representation of the function of a flapper valve.

Practical experience and theoretical strength calculations serve as the basis for determining the thickness of the valve and solving certain design problems. Strain measurements made on the surface of the valve reed indicated how complex the loading geometry is under operating conditions (2). The problem posed to the designer is to relate calculated or measured stresses and strains to the fatigue properties of the valve steel.

From a strength point of view, the valve reed is treated as, for example, a prismatic beam or plate of a given size, shape etc. In reality, it contains external and internal defects which make the stress peaks at, for example, surface scratches, blanking marks, rolling defects and structural inhomogeneities higher than those which are calculated or experimentally measured in the surface of the valve reed. The local elevation of the stress level at an external or internal notch site can give rise to local plastic deformation in the material and can initiate a fatigue crack. The initiation stage is considered to be at an end when crack growth is controlled by the normal stress perpendicular to the plane of the crack. The fatigue crack grows to a length at which the fracture toughness of the material is reached and the valve breaks.

4 EXPERIMENTAL METHOD

Fractographic studies were carried out using a JEOL, JSM 50 A scanning electron microscope (Fig. 2). Where necessary, the fracture-starting structural inhomogeneities were identified qualitatively using an energy-dispersive microprobe (EDAX 707), which was used in combination with the microscope.

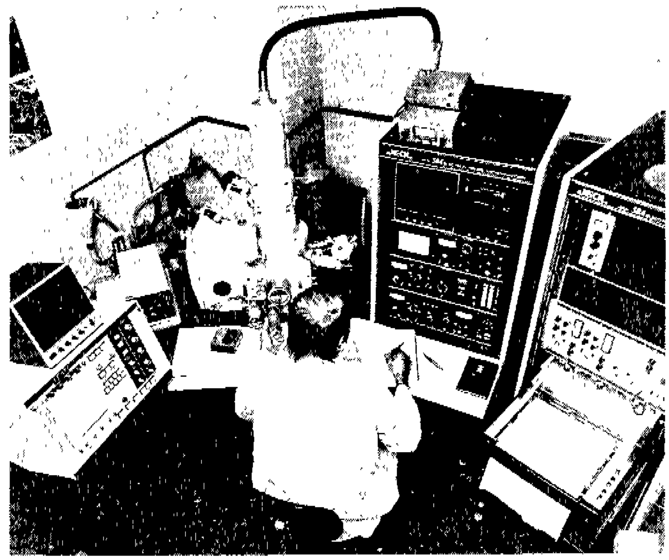

Fig. 2 JEOL JSM 50 A scanning electron microscope

5 RESULTS AND DISCUSSION

5.1 Initiation of fatigue fracture at non-metallic inclusions

Hard and brittle slag inclusions were identified as the starting points for fatigue failure. The closer such inclusions are to the surface, the greater their notch effect (3, 4).

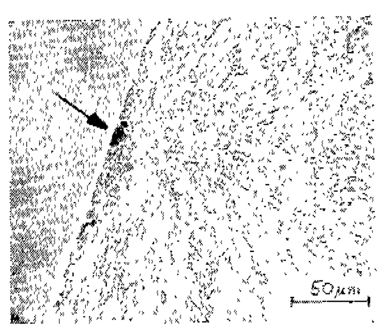

Fig. 3
Crack initiation at a brittle oxidic inclusion.

Fig. 3 shows an oxidic slag inclusion of the Al_2O_3-type which served as a fatigue crack starter. An area of stable crack growth can be observed around the inclusion.

Fracture initiation at plastic inclusions of the MnS or $MnO-SiO_2$ type was not encountered in the cases studied. These inclusions occur in the form of thin bands oriented parallel to the rolling direction.

5.2 Fracture crack starts at surface defects originating from strip manufacture

Surface defects such as scratches and rolling defects can affect the service life of the valve. Fig. 4 shows a valve reed which broke in the middle above the hole. Fatigue fracture was initiated at a longitudinal scratch (Fig. 5, 6) perpendicular to the maximum stress under the loading. The appearance of the edge is similar to the tumbled edge (Fig. 7) with blanking marks. However, the surface, which exhibits pronounced polishing scratches, seems to be unaffected by tumbling. Ineffective tumbling and high operating stresses can be regarded as a contributory cause of failure.

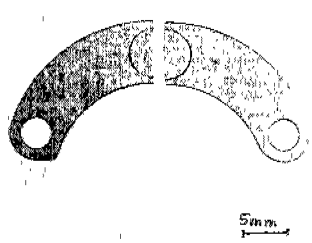

Fig. 4
Valve fracture.

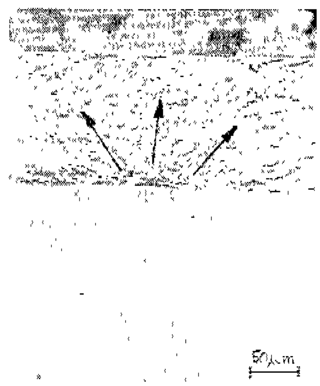

Fig. 5
Fatigue crack which started at surface scratches.

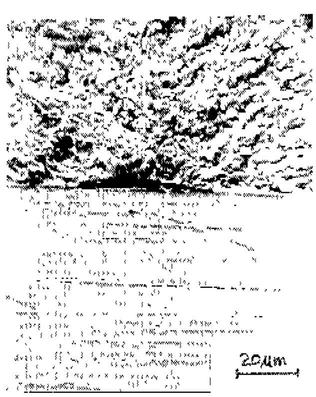

Fig. 6
Close-up.

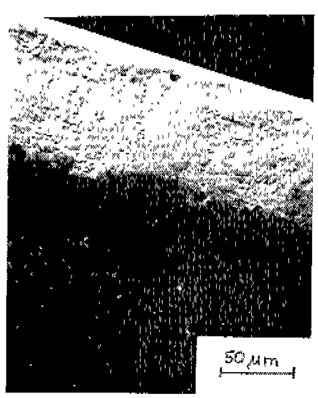

Fig. 7
Blanking marks in the edge after tumbling.

Another example in which the crack follows the surface scratches is shown in Fig. 8. The part was a valve in the compressor of a pneumatic vehicle brake.

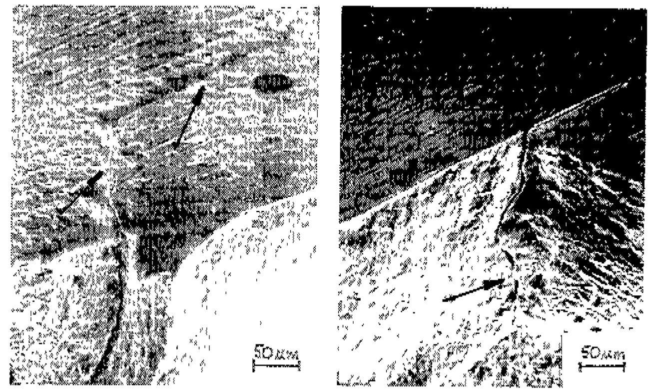

Fig. 8
The crack follows the surface scratch.

Heavy transverse scratches have a devastating effect on service life (see Fig. 9). The scratches are probably of mechanical origin. Such defects are difficult to eliminate by tumbling due to their depth.

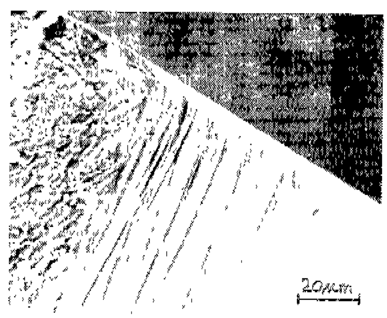

Fig. 9
Fatigue failure started at transverse scratches.

The surface of the valve may contain rolling defects (Fig. 10) rolled-in metal fragments (Fig. 11) and similar defects which may provide starting sites for fatigue cracks. Suction valves shown in Fig. 25 were put into service directly after blanking, i.e. with untumbled edge and surface. Failure was caused by fatigue fracture which started at defects originating from rolling (Fig. 12). The stable growth of the cracks is evident in the pictures.

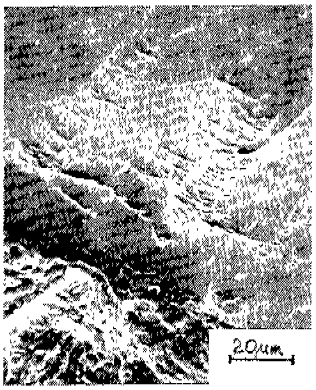

Fig. 10
Rolling defect.

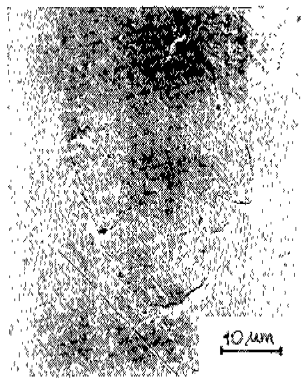

Fig. 11
Metal fragment pressed into the surface of the strip.

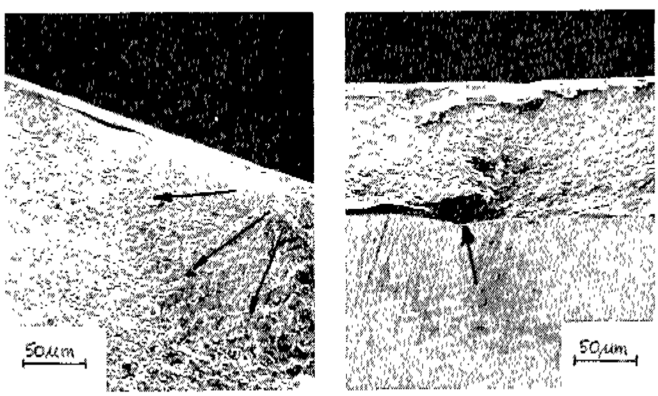

Fig. 12
Crack initiation and stable crack growth at rolling defect.

5.3 Defects introduced during the manufacture of the valve reed

Blanking is used in most cases for producing valves from steel strip. A blanked edge contains burrs, cracks and jagged notches (Fig. 13).

Improper blanking technique may result in such defects reaching a size of approx. 100 µm. A fatigue failure which started at notches left by blanking is shown in Fig. 14.

During tumbling, which is performed to improve the surface of the valve, edge and surface roughness is eliminated by material removal, which is greatest on the edge and less on the surface. In addition, compressive stresses are introduced (5) which can reduce applied tensile stresses.

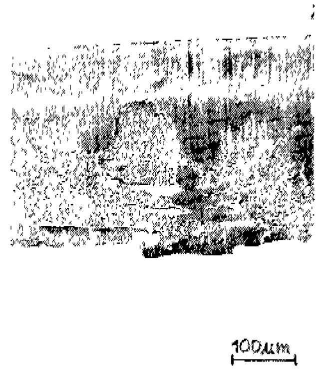

Fig. 13
Blanked edge.

Fig. 14
The failure started at notches left by blanking.

The resultant quality of the surfaces is primarily dependent on the edge and surface topography which is obtained after blanking. The surface quality of the strip itself is also very important. The problem is accentuated by more complex valve designs, with for example, slots or holes (Fig. 15).

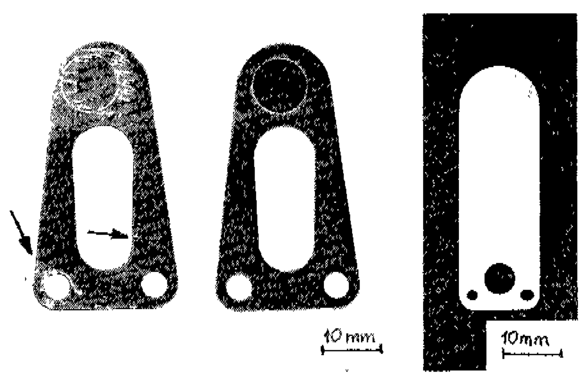

Fig. 15
Valve reeds with slot (left) and hole (right). Arrows indicate fatigue fracture.

Based on experimental results, Gluck and Cohen (6) obtained a significantly longer service life for a refrigerant compressor fitted with a valve without a slot as compared with a somewhat modified compressor fitted with a slotted valve. The following example demonstrates the practical problems involved in tumbling slots or holes. A fatigue crack which started in the inner edge of the slotted valve (Fig. 15) is shown in Fig. 16. Despite the fact that the outer edge of the valve exhibited clear evidence of tumbling (Fig. 17), the inner edge is laced with cracks and notches similar to a blanked edge without tumbling. Furthermore the edge profile indicates, that improper blanking technique can be regarded as a contributory cause of failure (Fig. 16).

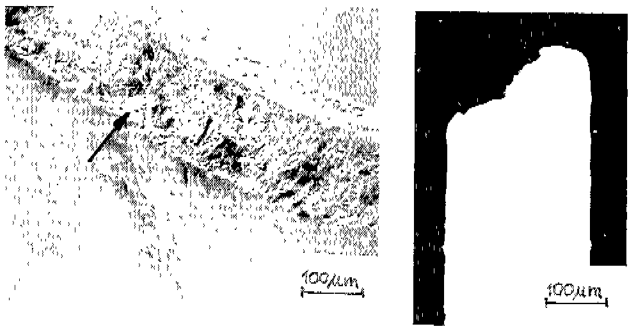

Fig. 16
The fatigue cracks started in the inner edge (left). Profile of the inner edge (right).

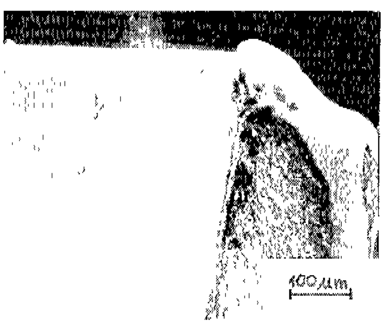

Fig. 17
Outer edge with partially worn fracture surface.

Slots or holes which are made to reduce the flexural resistance of the component substantially reduce its service life as well with their defect-riddled edges. Note that this part of the component is subjected to the greatest bending moment.

5.4 Surface damage introduced during service

Investigation of valve reeds after extended periods of service (Fig. 18) disclosed shallow grooves in the reed surface which contacts the valve seat and the stop (Fig. 19). These grooves are probably due to wear. Study of these defects revealed a copper desposit and a rounded surface topography without any jaggedness or notches. Crack initiation or fracture has not been found in the worn surfaces.

If any foreign particle should land between the contact surfaces, a notch could form. Figures 20 and 21 show the start point and the stable crack growth of the fatigue failure which was formed on the contact surface between the valve reed and valve seat.

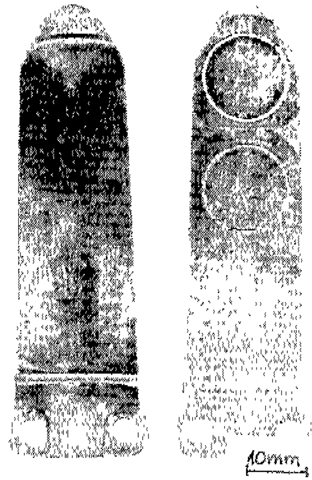

Fig. 18
Valve reed after 6 years of service.

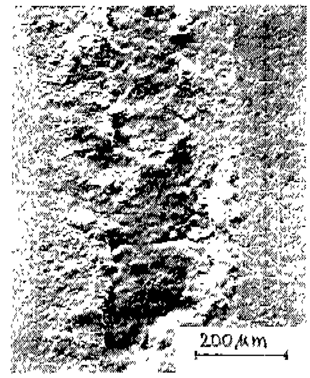

Fig. 19
A copper desposit was found in the groov.

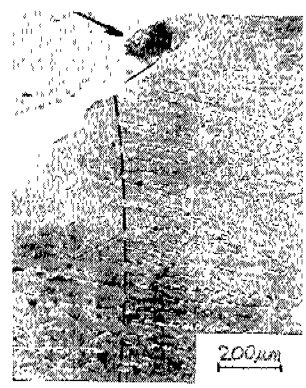

Fig. 20
Notch formed on the contact surface (dashed line).

Fig. 21
Fatigue crack which started at surface notch.

5.5 Corrosion

During long-term tumbling, which normally takes place in a moist atmosphere, corrosion attack can occur. If the valve operates in a damp environment, for example when condensate forms in air compressors, the reed may be damaged by rust or by corrosion (9). Fig. 22 and 23 show a part of a broken valve and a detailed close-up of the fracture surface. The reason for the failure was fatigue fracture which started at surface defects caused by corrosion. As is evident from Fig. 23, the notch was very shallow, but note that the crack was initiated and grew stably over a broad area. The valve material was a 1 % carbon steel.

The fatigue fracture shown in Fig. 24 originated as indicated by the fatigue markings, at the corrosion pit. The pit was approximately 30 µm deep.

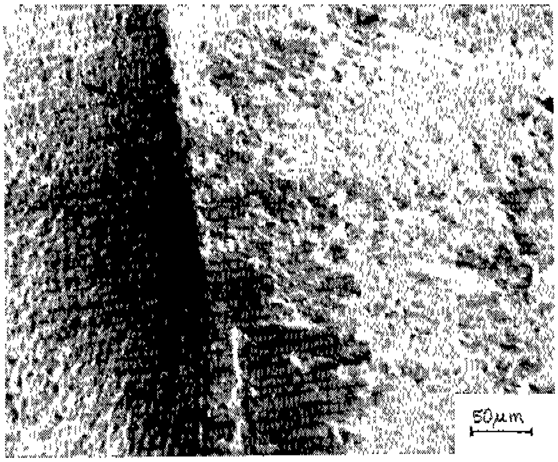

Fig. 22
Corrosion damage on the surface of the reed. Arrows indicate the stable crack growth.

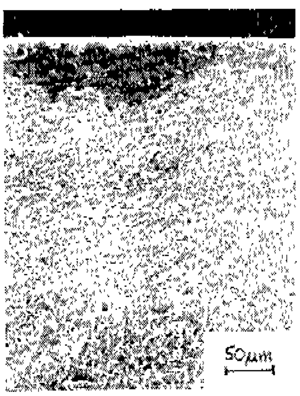

Fig. 23
Fatigue fracture initiated at shallow corrosion pits.

Fig. 24
Fatigue crack in a reed valve originating at a surface pit and propagating through the thickness.

For applications in corrosive conditions, the material should be chosen especially carefully. Service life is substantially prolonged by the use of martensitic stainless steel, UHB Stainless 716 containing 0.35 % C, 13 % Cr and 1 % Mo.

5.6 Overloading

The compressor designer strives for reeds which are as thin as possible in order to keep valve resistance low and increase efficiency. If we regard a valve reed as a plate freely carried by a circular valve seat the maximum stresses σ_{max} in the centre above the seat can be approximated using the following equation (7):

$$\sigma_{max} = \frac{3\nu D^2}{8 t^2} \cdot P \left(\frac{3}{\nu} + 1 \right)$$

ν Poisson's ratio

P Working pressure

D Diameter of the valve opening

t Thickness of the plate

As is evident, thickness and the diameter of the opening are dominant factors which determine the stresses in the reed. If the strength of the material is exceeded, a failure is obtained in the centre of the reed (Fig. 25 and 26), where the highest stresses occur when the reed is bent down. This can be caused by overloading or be due to the failure of other parts of the compressor. In the literature, these stresses are called flexural "overshoot" stresses (8).

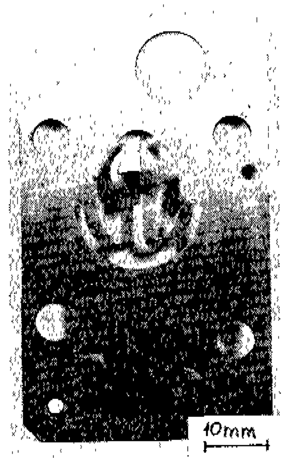

Fig. 25
Appearance of the fracture in the centre of the reed.

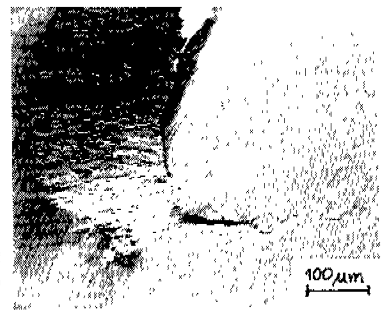

Fig. 26
The material slips after the start of the fracture.

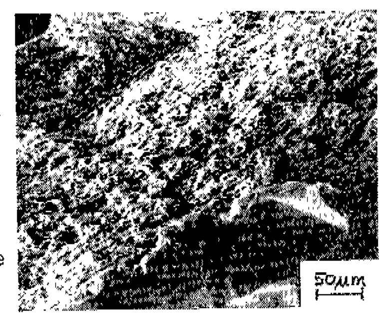

Fig. 27
Ductile fracture with dimples. The fracture surface is partially worn.

Fractographic study on overloaded valve only revealed ductile dimple fractures (Fig. 27). Such fractures are due to obviously undersized valves. No evidence of any fatigue crack starters was found.

6 THE RELATIVE SEVERITY OR "NOTCH EFFECT" OF DIFFERENT TYPES OF DEFECTS FOUND IN VALVES

The fatigue strength of a machine component is entirely dependent on the "weakest link", which is represented by the severest defect at the most heavily loaded site.

Removing such fatigue crack starters will prolong the fatigue life of the component. It is therefore important to determine how severe a certain type of defect is. In order to get an idea of the importance of the defect to the function of the component, information on the frequency of occurrence of the the defect is also important. The frequency of occurrence of a certain type of defect is affected by many factors, such as the design of the compressor and the valve, choice of material, loading geometry, desired service life etc.

A crack is most dangerous if it is located in a plane perpendicular to the direction of maximum stress. Theoretical notch effect increases as the depth and sharpness of the tip of the crack increase. In practice, it is very difficult to measure these parameters exactly and thereby quantitatively define the notch (10). Furthermore, the stress pattern around an unknown defect in a valve is very complex. However, it is possible to make a qualitative estimate of the notch effect of different defects. The results are shown in Fig. 28 and are based on fractographic studies.

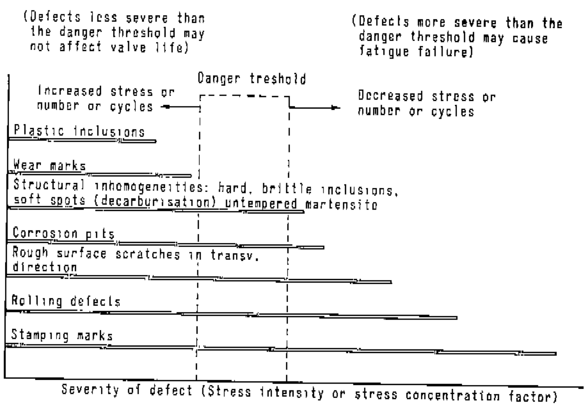

Fig. 28
Graphical representation of the range of relative severities of different types of defects found in valves.

Elongated plastic slag inclusions and defects with well-rounded surfaces, such as shallow grooves caused by wear proved to be less harmful from the viewpoint of crack initiation. Hard oxidic inclusions, on the other hand, are potential fracture crack starters. Their angular morphology gives them higher theoretical notch effect. Compared with other defects, however, the probability of finding an initiating inclusion is very small, while the frequencies of blanking (stamping) marks (Fig. 13, 16) rolling defects, (Fig. 10 - 12) and surface damages of mechanical origin (Fig. 9) are significantly higher. Moreover, these defects occur on the surface, where their damaging effect is greatest.

These latter defects lie above the "danger threshold" and are considered to be the most important defects. In practice, there exists a competitive relationship between different types of defects. The "danger threshold" level varies with valve design, operating conditions, material etc. At high stresses or high number of loading cycles less severe defects can also cause fracture.

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