Shot Peening to Prevent Stress Corrosion Cracking and Corrosion Fatigue Failures of Austenitic Stainless Steels.

K. Risch, Hoechst AG, Werkstofftechnik, Frankfurt (M) 80, FRG

1. Introduction

In corrosive environments austenitic CrNi and CrNiMo stainless steels are normally used in their passive state where an extremely thin layer of surface oxide protects the material against active dissolution. Yet, under the combined action of tensile stresses and several media cracking as a form of localized corrosion may occur. Depending on whether the loading is applied in a monotonous, in practice mostly static, or in a cyclic way, the phenomena are referred to as stress corrosion cracking (SCC) or corrosion fatigue (CF), respectively. Under certain conditions, shot peening provides a useful and efficient means to prevent these types of damage by introducing internal compressive stresses into a zone immediately below the surface. The present paper demonstrates advantages and limitations of shot peening by some selected examples.

2. Stress corrosion cracking

In austenitic stainless steels, the majority of SCC failures is initiated under the influence of chloride containing solutions. Chloride concentrations as low as 0.1 mg/l (2.8 x 10^{-6} moles/l) are sufficient to cause SCC, provided that the other relevant parameters, like pH-value, temperature and the free corrosion potential of the steel, attain adequately critical values. The lower the aggressiveness of the medium, the higher is the mechanical loading needed for SCC to occur. The stresses arising from service of the apparatus only play a minor part. Rather, internal tensile stresses as a remainder of the fabrication process turn out to be the crucial factor (1). In order to be able to correctly judge the risks of SCC in every individual case and to take suitable remedial measures, test procedures adapted to the problem are obviously necessary.

2.1 Residual stresses by forming and by welding

Forming and welding processes produce residual stresses throughout the cross-section of the workpiece. Annularly grooved and welded plates (AGWP) as depicted in Fig. 1 are often used to model the resulting state of stress. The shrinkage of the weld metal in the groove during solidification induces radially directed internal stresses of the tensile type outside the annular weld. Together with the action of a medium containing chloride ions these conditions led to the circular crack pattern shown in Fig. 1. From this finding a decrease in stress from the weld to the outer margin of the plate may be derived. Similar lowering of the stress level is observed in the direction perpendicular to the surface into the bulk of the sample. This is demonstrated by the hardness, determined in a cross-section near to the external edge of the weld (Fig. 1, right). The Vickers penetration number V. P. N.

(D. P. H., 0,25 N) is plotted as a function of distance from the surface in curve 1 of Fig. 2. The highest value (300) was found in a depth of 10 µm being the smallest distance from the surface accessible to the measuring technique. Proceeding into the depth of the sample, the V. P. N. decays to reach 225 at 200 µm, a hardness still higher than that of an unwelded sheet in the as-received condition (V. P. N. <200).

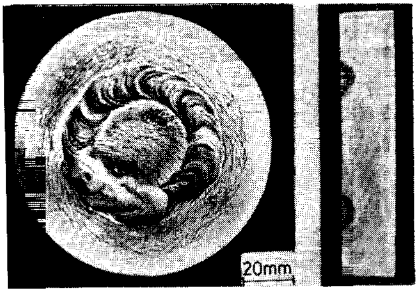

Fig. 1: SCC of an annularly grooved and welded plate of CrNiMo steel 1.4571; Hexachlorobutadiene with 2 % water; ϑ = 150 °C.

For quite a long time, it has already been a well known fact that shot peening is very effective in protecting samples of the type shown in Fig. 1 from SCC (2). To achieve a sufficient result, the necessity of a perpendicular impact of the impinging particles is

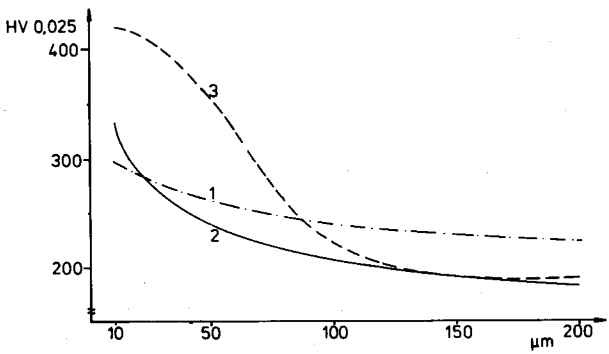

Fig. 2: Microhardness (D. P. H., 0,25 N) as a function of distance from the surface of specimens (CrNiMo steel 1.4571) after different treatments.
1: welded; 2: coarse ground (c. g.);
3: c. g. and shot peened.

generally emphasized, a demand that in practice is met, if at all, only under great expenditure due to geometric restrictions. In order to clarify the influence of the angle of impact, AGWP were treated by glass beads having diameters of 100 to 200 µm and using a blasting pressure of 6 bars. Angles of 90, 70 and 50 degrees were adjusted and the jet was maintained until the welding scale had been completely removed. In the strong test medium listed in Fig. 1 as well as in boiling 42 percent $MgCl_2$-solution, all of the samples proved to be immune against SCC. These results greatly enhance the practical realization of shot peening as a remedy against chloride induced SCC (1;3).

2.2 Residual stresses by surface finishing

Apparatus construction frequently necessitates finishing of larger surface areas by means of a manual grinder to smoothen repairings, to level weld reinforcements or to remove scale and spots of weld slag. As a rule, grinding wheels of coarse grain size, mostly 24, are used for that purpose. Practical experience (4) as well as laboratory investigations (3) clearly demonstrate that higher in-

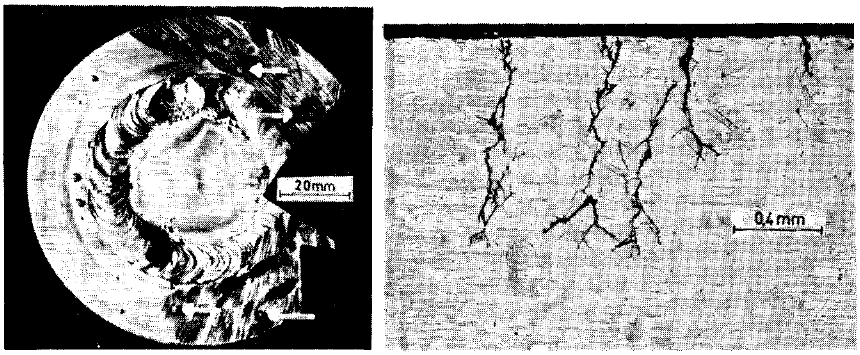

Fig. 3: SCC in the coarse ground zone: locations of cracks appearing as bright spots are marked by arrows.

ternal tensile stresses are introduced by this surface treatment than by welding. As an example, in the left part of Fig. 3, an AGWP is shown the surface of which was partly ground using grain 24. Under the action of a relatively weak corrodent - acetic acid solution of pH = 3 containing 100 ppm of Cl^-- SCC initiated at 130 °C and, after only 5 days of exposure, penetrated the sample to a depth of 1 mm (see right hand side of Fig. 3). The cracks had originated within the ground area, exclusively. On the surface, crack mouths appear as bright spots surrounded by dark circles. The lower level welding stresses had not been sufficient to cause SCC. Tool marks of other cutting treatments, like drilling, turning or milling may provoke the same detrimental effects as grinding.

From the result described above the conclusion can be drawn that specimens of the type shown in Fig. 1 are not suitable for the examination of SCC susceptibility by weakly attacking corrodents. Rather, a surface prepared by coarse grinding has to be exposed to the medium. This demand is fulfilled with strips of sheet metal as depicted in the left and central portion of Fig. 4. After exposure, the specimens are bent to find whether cracking has occurred (see Fig. 4, right). The increase in hardness coming along with the residual tensile stresses by grinding is plotted in curve 2 of Fig. 2. V. P. N. was determined at the narrow side of a strip specimen (Fig. 4, centre).

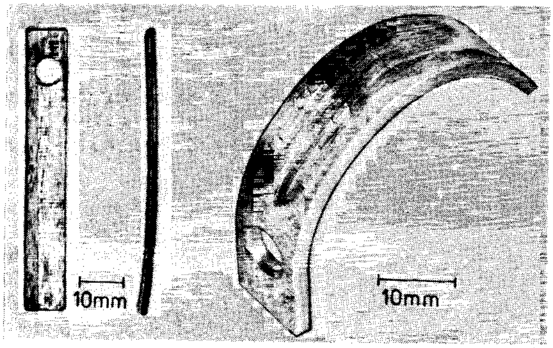

Fig. 4: Left and centre: aspects of a new specimen typ for SCC testing; right: bent specimen after exposure; transverse SC cracks.

A microhardness as given in curve 2 agrees well with the experimental finding depicted in Fig. 3. Obviously, in the plot, the residual tensile stresses generated by coarse grinding rapidly decay with growing distance from the surface. Controlled pickling which removes the highly stressed zone of material presents a very simple method to prevent SCC in weak corrodents. The thickness of the layer to be dissolved depends on the environmental service conditions. It can be checked by strips treated in an appropriate manner (1). However, pickling although being very economical fails as protection technique against strong corrodents, e. g. boiling 42 percent $MgCl_2$-solution, because then quite low internal tensile stresses cause SCC.

Coarse ground surface regions to be exposed to strong corrodents are entirely protected at a higher cost by shot peening. A plot of microhardness brought about by the residual compressive peening stresses is shown in curve 3 of Fig. 2.

2.3 Limitations by pitting

In chloride containing media, austenitic stainless steels are equally prone to pitting whether superficial residual stresses of compressive or of tensile type are present. If, in addition, the requirements for the onset of SCC are met, both forms of corrosion proceed at the same time. As an example of coinciding attack Fig. 5 shows a section of the wall of a vessel with a heating

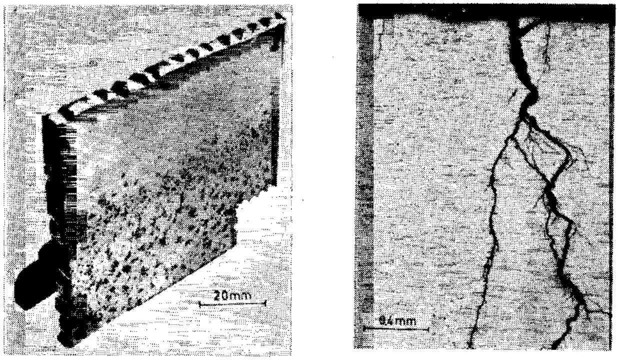

Fig. 5: Section of a vessel made of CrNiMo steel 1.4571 with a steam jacket welded onto the outside; SCC in the welding zone.

jacket welded onto its outside. Numerous, sometimes very fine pits appear all over the heat transferring zone. In the central part of the section, SCC resulting from residual welding stresses had entirely penetrated the wall thickness. In this case, shot peening could have prevented cracking only for a period necessary for pits to propagate through the layer of compressive stresses. Thus in cases when finely dispersed pinhole type pitting is accepted in order to circumvent the additional costs necessary for a higher alloyed material shot peening may loose its efficiency.

3. Remedial measures against passive state corrosion fatigue

In contrast to SCC, CF does not require the presence of specifically acting anions. This holds for austenitc stainless steels, too. Cyclic mechanical loading that leads to a continuously repeated destruction of the protective passive film by slip steps emerging from the surface is a prerequisite. The irreversible loss of metal due to corrosion and passive film repair during each slip event leaves a crack nucleus acting as initiation site for subsequent fracture. Ways to combat CF are manifold, for instance, precautions taken during design and construction of the component, selection of a material with high fatigue limit or, following a recent finding (5), using a steel of high chromium content thus accelerating the repassivation rate. Clearely stopping the active slip lines before they emerge from the surface offers the most efficient preventive measure. By introducing compressive residual stresses shot peening is excellently suited for this purpose. To obtain the desired result, in the case of CF the angle of impact has to be 90 degrees. Moreover, the glass beads should be allowed for single use exclusively, because sharp-cornered fragments leave notches in the surface thus impairing the improvement by shot peening. To know a priori the regions especially susceptible to CF on the component may considerably lower the costs for a peening treatment.

3.1 Base metal to weld transition

A great number of CF failures in the chemical process industry involves the transition region from a weld to the base metal. The agitator wing in Fig. 6 contains four welds each one joining

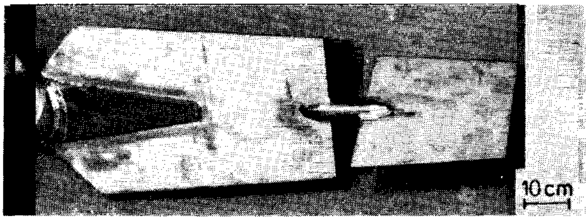

Fig. 6: Part of a failed agitator (CrNiMo steel 1.4571).

material of different thickness. In a crystal suspension, along these joints forming regions of varying stiffness cracking had occurred under swelling bend loading (s. Fig. 7). Without exception, the fissures exactly follow the undercutting. The steel did not show any traces of corrosion. On the fracture surface, lines of crack arrests appear which are a common feature of pure fatigue fractures, too. But, next to the transgranular main crack,

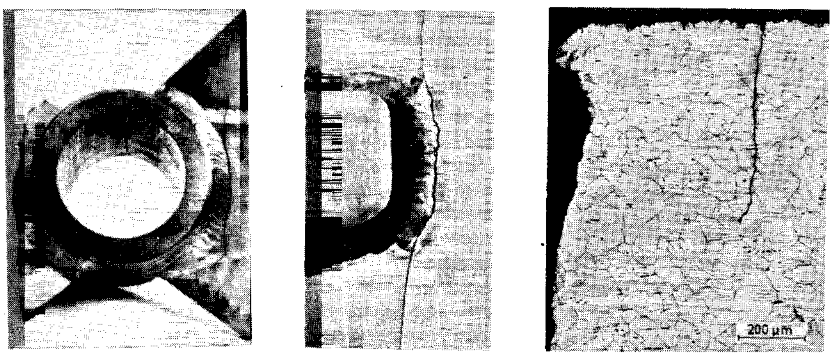

Fig. 7: Left and centre: cracks originating from undercuttings; right: metallographic section taken perpendicular to the fracture surface.

the optical micrograph of a metallographic section taken across the crack path reveals a secondary fissure of the same type, thus unequivocally furnishing the proof for CF. In accordance the part had failed after a period corresponding to more than 2 x 10^7 load cycles normally taken to determine fatigue strength. The cracks always started in the transition zone between weld and base metal. The different stiffness behaviour of the rolled sheet material and the grain flow of the weld gives rise to an inherent metallurgical notch which during bending suffers from the highest momentum. This fact holds even in the case that the thicknesses of the different parts of the joint had been approximated to each other. Modifying the construction and removing the undercutting did not overcome the problem. Only shot peening by means of glass beads of 100 to 200 µm size and a blasting pressure of 6 bars was able to bring complete remedy. Before the shot peening, times to failure of one year were common whereas thereafter, in the course of ten years, further damages were totally absent.

3.2 Interaction of cyclic loading and superficial residual tensile stresses

In case of interaction of cyclic loading with high internal tensile stresses introduced into a layer just below the surface during a mechanical cutting process, high susceptibility to CF has to be taken into account. As an example, Fig. 8 shows a piece of

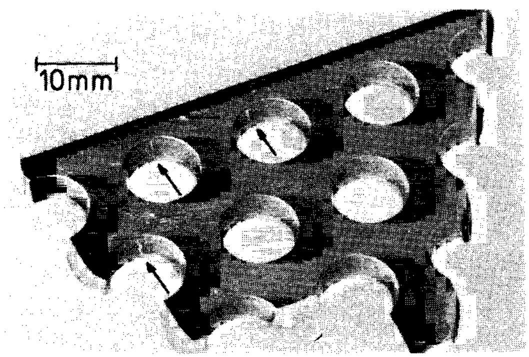

Fig. 8: Section of punched perforated plate made of CrNi steel 1.4541; left: fractured flanges; incipient cracks marked by arrows.

punched perforated sheet material with three fractured flanges on the left and three incipient cracks marked by arrows. In the cylindrical walls of the holes, punching had left high tensile residual stresses upon which, during service, a swelling bend loading was superimposed with the axis lying in the direction of the cracks. A similar situation arises in the periphery of holes drilled or punched into trays of distillation columns. The rectangular intersection of sheet surface and cutting face seriously interferes with the demand of producing defined compressive residual stresses by shot peening. Partly streaking of the surface by the peening particles even creates residual stresses of tensile type. Consequently, these regions would have to be carefully rounded by an awkward treatment only possible with sheet material of relatively high thickness. In addition to these difficulties considerable costs have to be taken into account when shot peening small punched holes present in an amount as in the example of Fig. 8. In this case recrystallization annealing provides a better means to eliminate detrimental fabrication stresses (5). In this way the lifetime of sheets as in Fig. 8 formerly ranging from 1 to 2 years was prolonged to such an extent that during 10 years of service cracking could be completely avoided.

References

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