THE 7th INTERNATIONAL CONFERENCE ON SHOT PEENING
ICSP 7
INSTITUTE OF PRECISION MECHANICS WARSAW, POLAND

EFFECTS OF PEENING ON STRESS CORROSION CRACKING IN CARBON STEEL

D. Kirk and P. E. Render
Coventry University, Coventry, U.K.

ABSTRACT

Stress corrosion cracking is an inherent problem commonly found in most carbon steels. This research compares the susceptibility of mild, heat-treatable and surface-treated carbon steels to SCC and investigates the effect that shot peening has on retarding it. U-bend specimens of mild, case-hardened and heat-treated EN8 steels at known tensile stresses were tested in dilute solutions of strong mineral acids. Calibrating the stress applied to the specimens was done using an instrumented strain bolt. This enabled the tensile surface stress on the outer radius of the U-bend specimen to be measured and allowed accurate time-to-crack measurements to be made. Studies showed that material conditions, in terms of hardness, microstructure and heat treatment, greatly affected the susceptibility to SCC. It was also found that shot peening substantially reduced SCC susceptibility. Using U-bend specimens of martensitic, EN8 steel, immersed in 30% sulphuric acid and heated to 67° C, cracking at high stresses (approximately 90% of the material's elastic limit) occurred after hours, when peened, as opposed to minutes for the unpeened specimens.

KEY WORDS

Carbon steels, stress corrosion cracking, peening, residual stress, X-ray analysis, strain bolt.

INTRODUCTION

Stress corrosion cracking, (SCC), is the formation and propagation of cracks in metals by the simultaneous interaction of a sustained tensile stress and a corrosive environment[1]. It can induce sudden failure, often with dramatic results, even causing loss of life. SCC can occur after as little as a few minutes of exposure or even after years of satisfactory service. It is often found in the absence of any other kind of obvious corrosive attack.

The three pre-conditions necessary for SCC to occur are tensile surface stress, a corrosive environment and material susceptibility. The minimum level of tensile surface stress needed to initiate cracking is referred to as the "critical stress level" and the more that this value is exceeded, the shorter is the time to eventual failure, see Fig.1. Virtually all alloy systems are prone to SCC by specific corrodents under certain sets of conditions. Generally, the higher the strength of an alloy, the more susceptible it is to SCC. Alloys are generally more susceptible to SCC than are pure metals

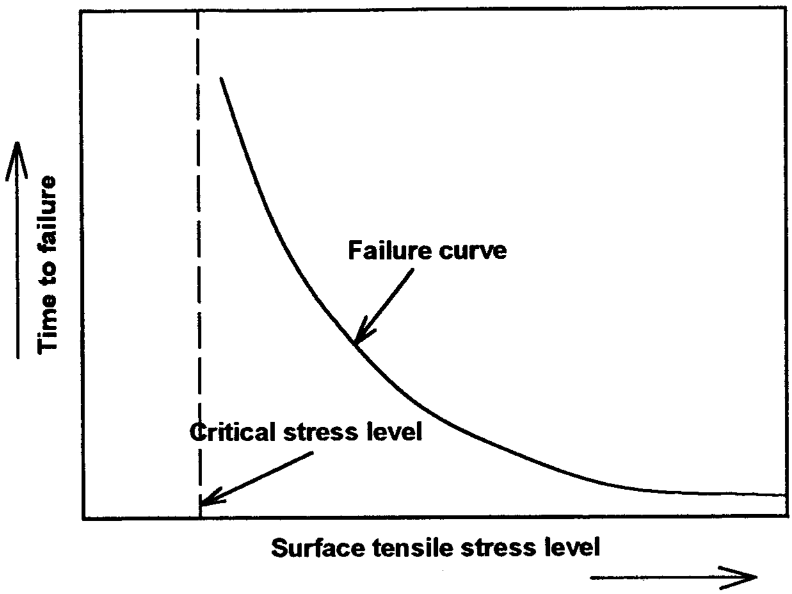


Fig.1 Schematic representation of stress/time relationship for stress corrosion cracking.

A material's resistance to SCC is often measured by the time it takes to either crack or to fail completely when a specimen is exposed to a specific environment at a constant stress. There are several measures currently employed to retard the effect of SCC. Amongst these are mechanical surface treatments, whereby compressive residual stresses are induced into the surface layer of the material. It is well known that cracks will neither initiate nor propagate in a compressively-stressed zone. Shot peening induces compressive surface residual stress, which, therefore, retards SCC[2,3].

This research aims to examine in detail the relationships that may exist between residual stress, applied stress and time to failure for a common grade of plain carbon steel tested in different states of heat treatment. Particular attention was to be paid to the developing an appropriate SCC test method.

EXPERIMENTAL METHODS

Specimens

There are many types of specimens and techniques that are used for testing SCC[4]. Of particular interest is the incorporation of a strain bolt[5], which allows continuous monitoring of applied loads, see Fig.2.

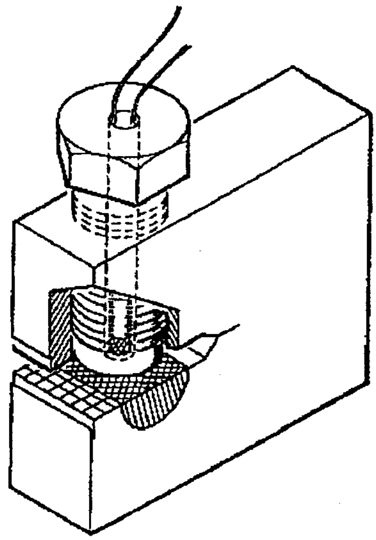


Fig.2 Strain bolt used to monitor applied loads on a pre-cracked wedge specimen.

Wedge-shaped specimens are, however, inappropriate for this research programme. Instead simple U-shaped specimens of either rectangular section mild steel (25mm x 3mm) or round section EN8 (12mm diameter) were used, incorporating steel strain bolts. The specimen shape is illustrated in Fig.3. The strain bolt consists of a standard bolt having been drilled to accept a linear strain gauge wrapped as a cylinder and cemented on the central axis.

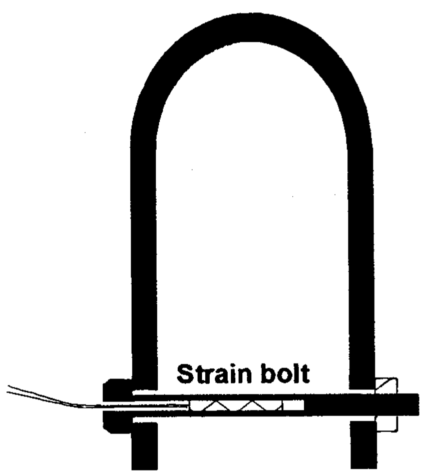


Fig.3 U-shaped SCC specimen with strain bolt.

Materials, Treatments and Solutions

The main objective here was to find the optimum material condition and corrosive medium combination needed to bring about rapid failure for a common, commercial, plain carbon steel. U-bend specimens of mild steel and EN8 (BS 970 080A35) steel were subjected to various heat treatment processes. The EN8 steel had a nominal composition of 0.35/0.45%C, 0.05/0.35%Si and 0.6/1.0%Mn. After being given the harshest heat treatment possible, by heating in a furnace and quenching in cold water, the strained specimens were suspended for up to several weeks in dilute solutions of strong mineral acids either at room temperature or at 67° C.

Stress/Strain measurements

The output from the strain bolts was fed to a standard strain bridge and thence to a chart recorder. Direct loading of the bolts in a tensile testing machine effected calibration of the bolts, for actual load against recorded strain gauge output. Tightening the strain bolt in a U-bend specimen induces a maximum strain on the outer surface of the U-bend. Strain gauges attached to that surface were used to provide calibration of induced surface strain against bolt output. Loaded specimens, without surface strain gauges, were tested for stress using a standard two-exposure X-ray diffractometer technique[6]. The X-ray technique was also used to determine the initial surface residual stress in specimens before loading via the strain bolt. The time-to-failure was assessed by continuously monitoring the strain bolt output from a loaded SCC specimen undergoing testing. When a significant crack appeared there was a corresponding drop in the load that was being applied to the specimen. The time for this drop was taken from the output of a chart recorder registering strain bolt output as a function of time.

Surface treatment of the specimens

Shot peening was carried out for a total time of 180 seconds, using S170 grade steel shot, 1.1kg/minute and 6.0 bar air pressure, holding the specimen at various distances away from the peening nozzle. Specimens were hand-held and each specimen was rotated slowly during peening, ensuring an even coverage of the shot over the "critical" region of the specimen.

Metallographic techniques and hardness

Metallographic specimens were prepared from both cracked and uncracked samples by sawing out, cutting to size and mounting in Bakelite. These mounted specimens were polished down to 1 micron and etched for 10 to 20 seconds in nital. The specimens were examined carefully under the microscope, using magnifications of up to x1000, with the aid of the image analysis equipment where necessary. Macro-hardness determinations were carried out using a Vickers hardness testing machine and micro-hardness determinations were made using a Digital Micro-hardness tester.

EXPERIMENTAL RESULTS

Strain bolt calibration

Initial calibration of strain bolts was effected by pulling the bolt in a tensile machine and measuring strain gauge output against applied load. Data for a typical strain bolt is presented in Fig.4. This shows the expected linear relationship.

On bridging the two arms of a mild steel U-bend specimen with the instrumented bolt, a linear relationship was obtained between the induced stress and the loading distance.

Stress measurement by X-ray diffractometry

The surface stress at the outside of a loaded mild steel U-bend specimen was measured using X-ray diffractometry[6]. Different loads were applied by means of a strain bolt. Fig.5 gives the measured values of stress and strain bolt output. With no applied load on the specimen the surface stress level was −199MPa, which corresponds to residual stress induced during manufacture of the specimen. That process, of bending a beam plastically, is a classic source of compressive residual stress on the outside surface of the beam.

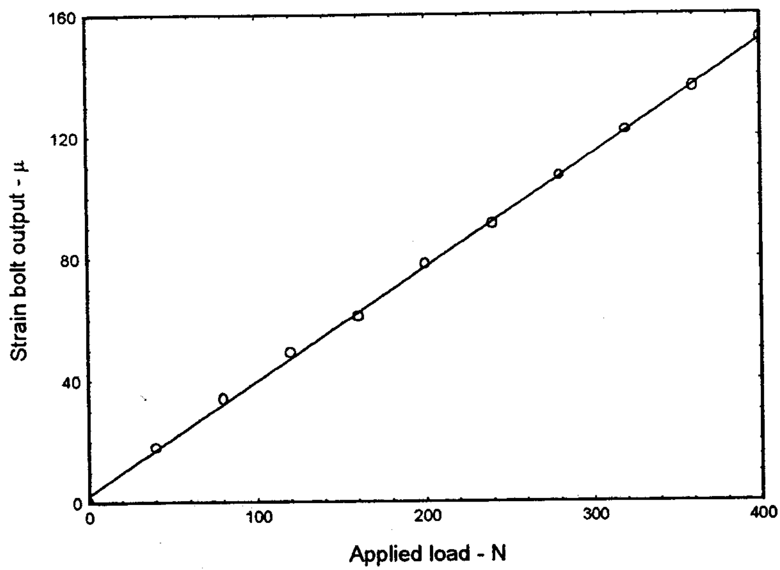


Fig.4 Relationship between applied axial tensile load and strain bolt output.

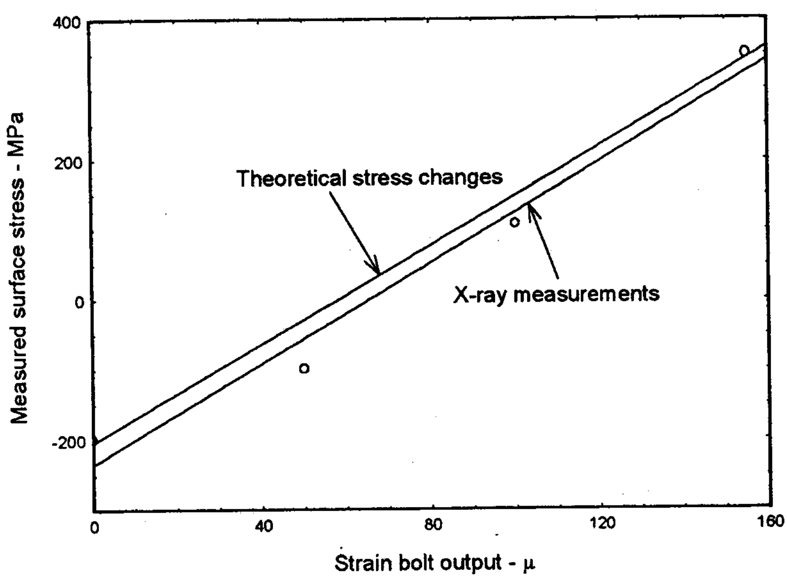


Fig.5 Surface stress level changes induced by loading a U-bend SCC steel specimen.

The results in this section show that the strain bolt can be used to apply known loads to a U-bend specimen but that the actual surface stress depends upon the initial residual stress level.

Applied surface stresses, σ, on a rectangular section U-bend specimen can be calculated using a simplified standard formula:

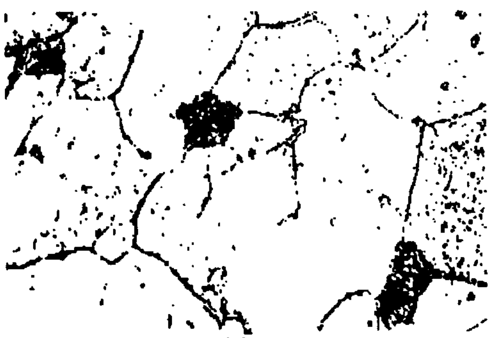
$$\sigma = 6.F.D/(w.t^3) \qquad (1)$$

where F = applied force, D = length of specimen arm up to the radius, w = width and t = thickness.

Values of surface stress change calculated using equation (1) are included in Fig.5.

SCC studies for Mild Steel

SCC studies were carried out on rectangular-section mild steel specimens loaded to 80% of the yield strength. The studies were carried out on steel in both cold-rolled and as-quenched conditions having hardness values of 224HV and 394HV for the two conditions respectively. Fig.6 shows the considerable difference in microstructure for the two conditions.


(a)


(b)

Fig.6 Microstructures of 0.1%C mild steel, x490, etched in Nital, (a) cold rolled with 12% pearlite in ferrite matrix and (b) quenched from 900°C with fine carbides in feathery ferrite.

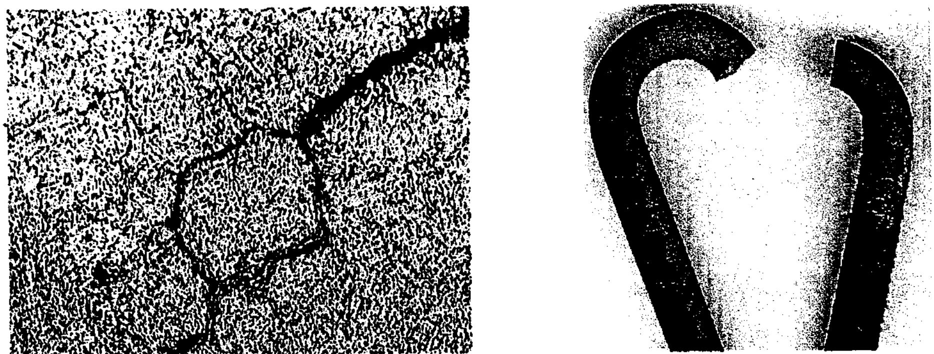
SCC tests were conducted using six different mineral acid combinations that had been reported to be effective in inducing cracking. Even with tests maintained up to four weeks no SCC cracking was observed. The tests did reveal, however, extensive surface corrosion for both structural conditions.

SCC studies for EN8 steel in heat-treated and shot peened conditions

SCC tests were carried out for EN8 steel specimens quenched from 1100°C into cold water giving a hardness of 841HV. This treatment was adjudged as being that which would impose the most sensitive condition on the steel. Preliminary tests showed that in this condition rapid SCC could be induced using a 30% sulphuric acid solution at 67°C.

Fig.7 shows the microstructure of the steel and two halves of completely failed round bar specimens. This is a fully-martensitic structure, untempered, and therefore contains very high levels of micro residual stresses. There is virtually no ductility and the steel will fracture at or just above its yield point.

Fig.8 shows the results of the SCC tests carried out on the EN8 heat-treated specimens. Stressing of the specimens is expressed as a percentage of the known fracture strength of the specimens. In spite of the limited number of measurements there is a clear indication that the failure characteristic is very similar to the classic trend shown as Fig.1.



(a) (b)

Fig.7 (a) Micrograph of EN8 specimen showing cracking through martensitic matrix, x150, Nital etch and (b) complete failure of SCC specimens, x0.5.

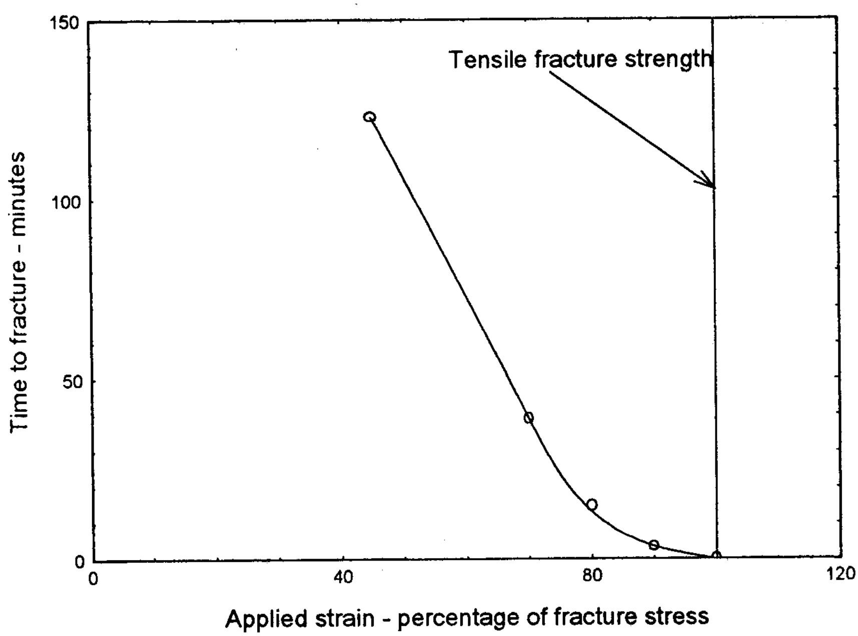


Fig.8 SCC tests carried out on as-quenched EN8 steel U-bend specimens.

The times to failure of five heat treated U-bend specimens of EN 8 steel, all stressed to 90% of their elastic limit, were 4, 3, 2, 5 and 3 minutes giving an average of 3.4 minutes. That result indicated that the test method was capable of reasonable reproducibility.

SCC study for shot peened specimens

Having established that the test procedure was capable of producing SCC in reasonable times for as-quenched EN8 steel specimens the influence of shot peening was then examined. Four different severities of peening were used on round-section, quenched, EN8 specimens loaded to 90% of the fracture strength. The times to cracking and peening conditions are given in Table 1. These show that peening increases the cracking time with increasing severity of peening. It should be noted that the severity of peening scale is qualitative and includes a consideration of the area being peened for the round bar sections.

Table 1 SCC cracking times for EN8 quenched steel specimens, 30% sulphuric acid at 67°C.

S170 6 BAR

Peening severity	Peening time - s	Peening distance - mm	Failure time - minutes
0	0	-	3.4
1	60	150	9
2	120	200	20
3	120	100	>60
4	160	100	>60

SCC tests with 30% sulphuric acid at room temperature (20°C) were expected to give longer cracking times than those shown in Table 1 for hot acid solution. Table 2 gives the results of tests carried out at room temperature, again at 90% of the tensile fracture stress. These again show the beneficial effect of shot peening on SCC times.

Table 1 SCC cracking times for EN8 quenched steel specimens, 30% sulphuric acid at 20°C.

Peening severity	Peening time - s	Peening distance - mm	Failure time - minutes
0	0	-	10
1	120	100	720
2	150	200	1800
3	180	100	2880

DISCUSSION

The main objectives of this research were to (a) develop a technique for assessing SCC that could be applied to simple shapes of specimens, (b) determine SCC conditions for plain carbon steels and (c) make a preliminary study of the effects of shot peening on SCC susceptibility. Each of these objectives has been achieved to a greater or lesser extent.

Technique for assessing SCC

There are several elements that are important for reliable testing of SCC times to failure.

(1) The maximum surface stress on the test specimen must be known. This has been shown to be a combination of residual stress and applied stress. X-ray analysis has shown that the combined stress can be determined with a good level of accuracy. The applied stress can be calculated to a good degree of accuracy by knowing the applied force, from the strain bolt output, and converting this into stress using equation (1). That conversion has been confirmed using X-ray diffraction measurements of total surface stress. Equation (1) is a simplified version of those that could have been applied. Separate studies have shown that the simplified version is more than adequate for this type of testing.

(2) The time at which failure occurs must also be known. Using a drop in output from the strain bolt as a measure of that time is more satisfactory than subjective visual judgements. A useful improvement on the use of a chart recorder would be to incorporate an analogue-to-digital converter feeding bolt output directly to a computer. Careful thermal insulation of the strain bolt

is important since heat transfer from hot test solutions induces strain in the bolt. This is reflected in a gradual change in strain bolt output rather than the rapid change that accompanies SCC.

(3) Specimen preparation is important. Rectangular section U-bend specimens are more amenable to X-ray measurement of stress than are round section specimens. Unfortunately commercial supplies of rectangular section carbon and alloy steels are limited in terms of available section shapes.

Determining SCC conditions for Plain Carbon Steels

It was found to be surprisingly difficult to induce SCC in plain carbon steel specimens even at very high levels of applied stress. Published studies had indicated that SCC susceptibility increases with severity of heat treatment. With this research it was found necessary to use the as-quenched state (most severe heat treatment) in order to induce SCC in short times. Normally EN8 steel would be tempered after heat treatment – reducing its sensitivity.

Stress/strain and environment conditions

The two parameters affecting failure rate for a given specimen were found, as expected, to be (i) surface stress level and (ii) concentration and temperature of test solution.

Effects of peening

Overall, the most important experimental observation was that peening significantly reduced the tendency of the steel specimens to SCC. This occurred for testing in 30% sulphuric acid solutions both at 67°C and at 20°C. These observations have therefore been consistent with previous published work regarding the beneficial aspects of peening in preventing or reducing the effect of SCC.

CONCLUSIONS

1. An experimental procedure has been established that allows SCC tests to be carried out on U-bend specimens of carbon steel.
2. The use of a strain bolt in conjunction with X-ray stress measurement enables known tensile surface stresses on the U-bend specimen to be applied and allows accurate, objective, time-to-failure measurements to be made.
3. Material hardness, microstructure and heat treatment greatly affect the steel's susceptibility to SCC. U-bend specimens of martensitic steel failed within minutes, specimens of mild steel under the same conditions did not fail at all.
4. The time-to-failure depends upon both the specimen's surface tensile stress level and the corrosive medium's temperature.
5. Shot peening reduces the susceptibility of quenched EN8 to SCC. Shot peened specimens took hours to crack as opposed to minutes for unpeened specimens.
6. Shot peening's effectiveness in retarding SCC is dependent on the variables of time, intensity and coverage.

FURTHER WORK

A number of improvements could be made on the experimental procedure. These include the employment of analogue-to-digital conversion and computer monitoring. Having now established a working procedure it will be possible to examine (i) the effects of shot peening quantitatively – in terms of severity of treatment, (ii) the influence of carbon and alloy content and (iii) heat treatment parameters. It will be particularly interesting to determine, quantitatively, the combination of residual stress and applied stress as a factor affecting SCC susceptibility.

REFERENCES

1. Evans U.R.: An Introduction to Metallic Corrosion, 3rd Edition, Arnold, 1981.
2. Obata, M, Sudo, A. and Matsumoto, J.: The Effect of Shot Peening on Residual Stress and Stress Corrosion Cracking for Austenitic Stainless Steel, Proceedings of Sixth International conference on Shot Peening, San Francisco, 1996, p.24-33.
3. Rahmatalla, H., Al-Rimawi, M and Al-Hadid, T.: Effect of Shot Peening on Stress Corrosion Cracking (SCC) of 7075-T6 Aluminium Alloy, ibid., p.184-191.
4. Sedriks, J.A.: Stress Corrosion Cracking Test Methods, NACE, 1990.
5. ibid., p.62.
6. Residual Stress measurement by X-ray Diffraction – Society of Automotive Engineers, J784a, 1971.