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Residual strength of maraging steel

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Surface crack tension (SCT) specimens of 18 Ni 1800 MPa grade maraging steel (parent metal and welded) were used to evaluate the residual strength in 0.015 and 0.03 m wide panels. For 0.03 m wide panels which satisfy infinite plate condition up to 0.006 m surface crack length, the residual strength variation between minimum and maximum crack sizes lie within 5% of the ultimate tensile strength (UTS) of weldments. Also for larger crack sizes both 0.015 and 0.03 m wide panels yields comparable values for residual strength. The results have significant bearing on flaw detection by non destructive testing (NDT) method which could be used for quality and reliability check on the fabricated component. Stress intensity values for these data makes an interesting observation on failure mode.

1. Introduction

The use of ultra-high strength steel like 18 Ni 1800 MPa grade maraging steel for launch vehicle application calls for fracture based design approach which necessitates determination of fracture parameters such as plane strain fracture toughness (KIC), sustained and cyclic stress crack growth rate (da/dN) and residual strength, σ_r. Some of the above parameters for this material have already been evaluated by the authors [1, 2, 3]. The evaluation of residual strength using surface crack tensile (SCT) specimens (parent metal and welded) is dealt here. ASTM [4] defines residual strength, σ_r, as the maximum value of the nominal stress neglecting the area of the crack, that a cracked specimen is capable of sustaining. For a surface crack tension (SCT) specimen, σ_r is the ratio of the maximum load (P_{max}) to the product of test section width (W) times the thickness, B i.e.

$$\sigma_r = \frac{P_{max}}{BW} \qquad (1)$$

σ_r represents the stress at fracture normal to and remote from the plane of crack. The residual strength will reflect the amount of margin of safety available for the designer for a particular flaw size, $a \times 2c$ (where 'a' is crack depth and '$2c$' surface crack length). This paper discusses the experiments carried out on SCT specimens of 18 Ni 1800 MPa grade maraging steel (Parent and weldment) to evaluate σ_r.

2. Experimental procedure

2.1. Specimens

Following ASTM E-740 [4] surface crack tension (SCT) specimens of 18 Ni 1800 MPa maraging steel were fabricated. This includes 0.015 m wide panels of both parent metal (longitudinal, LT, and transverse, TL, directions) and weldment and only 0.03 m wide panels of weldments. Panels 0.03 m which are wide satisfy the infinite plate condition, $W \geqslant 5 \times 2c$, (where W is width and $2c$ is surface crack length) upto $2c = 0.006$ m.

2.2. Surface crack generation

Ultimate tensile strength and fracture toughness values were evaluated using specimens fabricated from the same plate used for fabricating SCT specimens. INSTRON Model 8033 testing machine was used for the experiments. SCT specimens were subjected to three point bend fatigue loading cycle to generate surface cracks of various lengths starting from $2c = 0.003$ m. The crack growth on the surface was measured through a travelling microscope. The crack generation was done in as received condition (i.e. solution treated for parent metal and as welded for weldment) of the specimens which were then maraged at 753 K for 3 h. The ageing process incidentally acted as heat tinting and distinctly identified the crack profile.

2.3. Testing and crack size measurements

SCT specimens were subjected to tensile loading. The

TABLE I 18 Ni 1800 MPa Maraging steel, $W = 0.015$ m, parent metal (solution treated and aged); LT orientation

Sl. No.	Crack size $a \times 2c$ (m)	σ_r (MPa)	σ_{SCTS} (MPa)
1.	0	1860 (UTS)	–
2.	0.0013 × 0.0027	1850	1895
3.	0.0014 × 0.00295	1850	1900
4.	0.0015 × 0.0034	1840	1908
5.	0.0017 × 0.0038	1831	1916
6.	0.0017 × 0.0041	1820	1914
7.	0.0017 × 0.0043	1830	1932
8.	0.0018 × 0.004	1822	1913
9.	0.002 × 0.004	1830	1924
10.	0.0019 × 0.0048	1798	1925
11.	0.002 × 0.00485	1800	1902
12.	0.002 × 0.0045	1786	1930
13.	0.002 × 0.0044	1802	1918
14.	0.0022 × 0.0048	1783	1920
15.	0.002 × 0.005	1788	1925
16.	0.0022 × 0.0053	1771	1928
17.	0.0022 × 0.0057	1760	1923
18.	0.0023 × 0.0059	1760	1941
19.	0.0025 × 0.0058	1754	1938
20.	0.0025 × 0.0063	1711	1907
21.	0.0025 × 0.0065	1730	1940

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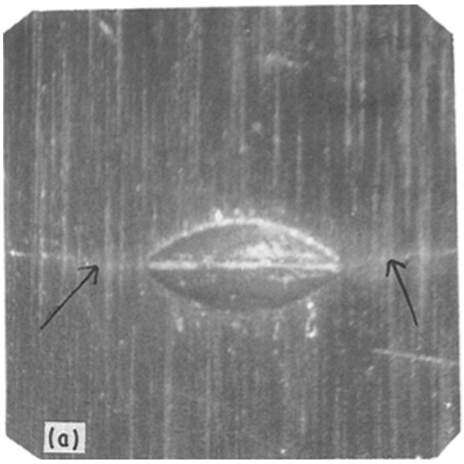

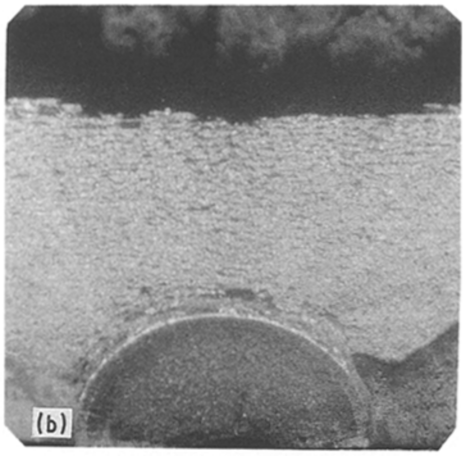

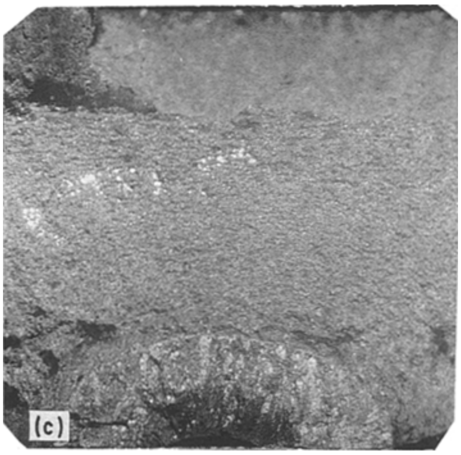

Figure 1 Crack profiles in SCT specimen (a) Starter notch (16x), 0.0009 × 0.0015 m, arrows indicate surface cracks grown. (b) Surface Crack profile in parent metal (10x) 0.0017 × 0.0042 m. (c) Surface Crack profile in weld (10x), 0.00157 × 0.0048 m.

loads corresponding to maximum point and 0.2% offset line from the extensometer plot of load vs extension were used for calculation of σ_r from P_{max}/BW. The broken halves of the SCT specimens were viewed under shadograph to get the crack profile and the crack sizes a and $2c$ were measured. Typical crack profiles are shown in Fig. 1.

3. Results and discussion

3.1. Residual strength

Table I gives σ_r values for parent metal ($W = 0.015$ m) in LT direction. The UTS (zero crack) of the material is 1860 MPa. The value of σ_r varies from 1850 MPa for 0.0013 × 0.0027 m flaw size to 1730 MPa for a crack of 0.0025 × 0.0065 m. The reduction in strength from UTS to σ_r with 0.0025 × 0.0065 m size flaw is 7%. The σ_r values for parent metal ($W = 0.015$ m) in TL direction are given in Table II. The variation of σ_r is from 1796 MPa for a crack of 0.0016 × 0.00385 m to 1713 for 0.0025 × 0.0068 m flaw. The reduction in strength from UTS to σ_r of 0.0025 × 0.0068 m flaw is about 8%. That is, for parent metal ($W = 0.015$ m) both LT and TL directions reduction in strength from UTS to σ_r with maximum flaw is about the same order.

The data generated on weldments assume larger significance since the rocket motor case is essentially of welded construction. So experiments were done on weldments for panels with $W = 0.015$ and 0.030 m. The data on autowelded specimens for $W = 0.015$ m is given in Table III. The value of σ_r is 1735 MPa for 0.0013 × 0.0027 m flaw and 1553 MPa for 0.0022 × 0.0068 m crack. The decrease in strength from UTS to specimens with largest flaw (0.0022 × 0.0068 m) is 9.5%. The 0.03 m wide panels satisfy the infinite plate condition i.e. $W \geqslant 5 \times 2c$ for all surface crack lengths upto 0.006 m. The data obtained from autowelded $W = 0.03$ m specimens is given in Table IV. The value of σ_r varies from 1700 MPa for 0.0095 × 0.0027 m to 1647 MPa for 0.0028 × 0.006 m. The

TABLE II 18 Ni 1800 MPa Maraging steel, $W = 0.015$ m, parent metal (solution treated and aged); TL orientation

Sl. No.	Crack size, $a \times 2c$ (m)	σ_r (MPa)	σ_{SCTS} (MPa)
1.	0	1860 (UTS)	–
2.	0.0016 × 0.0039	1796	1882
3.	0.0017 × 0.0042	1825	1921
4.	0.002 × 0.0047	1817	1945
5.	0.0021 × 0.0051	1753	1898
6.	0.0021 × 0.0052	1772	1919
7.	0.0025 × 0.0063	1732	1946
8.	0.025 × 0.0068	1713	1940

TABLE III 18 Ni 1800 MPa Maraging steel; welded; $W = 0.015$ m

Sl. No.	Surface crack size, $a \times 2c$ (m)	σ_r (MPa)	σ_{SCTS} (MPa)
1.	0	1720 (UTS)	–
2.	0.0013 × 0.0027	1735	1785
3.	0.0015 × 0.0027	1713	1772
4.	0.001 × 0.0028	1700	1734
5.	0.0011 × 0.0028	1752	1791
6.	0.0017 × 0.0038	1711	1787
7.	0.0015 × 0.0039	1706	1771
8.	0.0014 × 0.0039	1700	1765
9.	0.0015 × 0.004	1736	1812
10.	0.0016 × 0.0048	1711	1804
11.	0.0022 × 0.05	1666	1799
12.	0.002 × 0.005	1682	1804
13.	0.002 × 0.0053	1621	1749
14.	0.0022 × 0.0054	1654	1796
15.	0.0019 × 0.0057	1616	1743
16.	0.00226 × 0.006	1581	1773
17.	0.0027 × 0.0062	1590	1794
18.	0.0022 × 0.0066	1590	1797
19.	0.0022 × 0.0068	1553	1732

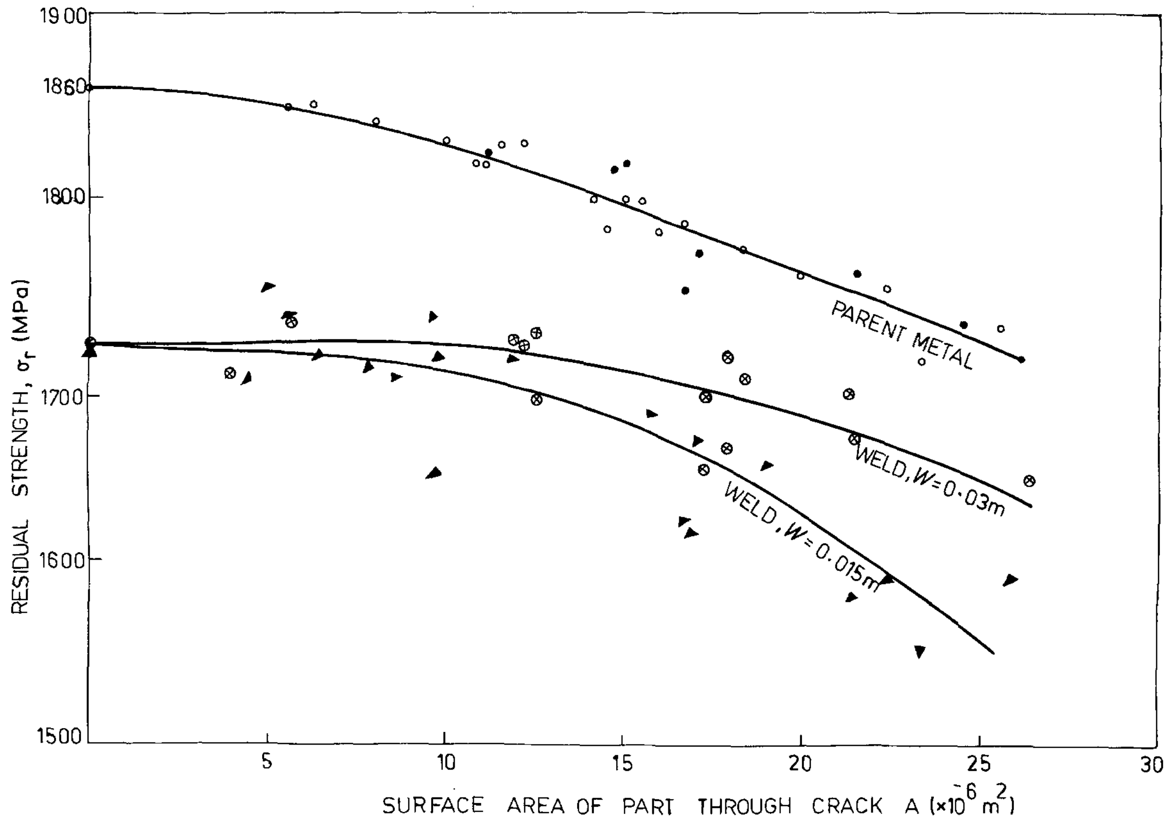

Figure 2 Residual strength against Crack Area for parent metal and weldments.

comparison of strength for zero crack to maximum crack size shows a decrease of 5%.

Fig. 2 shows the residual strength against surface crack area ($\pi ac/2$) for all the specimens tested. From the figure it can be observed that the residual strength values for both LT and TL direction of parent metal specimens show a decreasing trend as the area increases but with less scatter. A similar trend is observed for 0.015 m wide auto welded specimens. But for 0.03 m wide panel specimen the reduction in σ_r with area is not as steep as observed in other two areas. This is due to larger constraint imposed by infinite plate condition at the crack tip.

3.2. Stress intensity calculations

The stress intensity factor (SIF) for surface cracks is an important parameter in the design of pressure vessels since it helps to make reliable prediction of crack growth rates, burst pressure and σ_r for different flaws. Number of workers [5] have attempted to evaluate SIF for surface cracks. For SCT specimens the following equation [4] can be used to evaluate SIF:

$$K/\sigma_t(\pi a)^{1/2} = M/\phi \quad (2)$$

Where K is the SIF at the deepest point of the flaw; σ_t is uniform tensile stress, a is a crack depth, M is magnification and ϕ is shape factor for elliptical crack.

Residual strength, σ_r values from the present data is used as σ_t in the above equation to arrive at SIF at the deepest point in order to understand the fracture characteristics of the material. Since a/ϕ^2 is a good measure of crack size and SIF is a measure of resistance by the material for crack growth, a plot is made between SIF and a/ϕ^2 as shown in Fig. 3. For surface crack configurations number of investigators have derived R-curve [6]. Incidentally the experimental plots in Fig. 3 can also be considered as R-curves generated by multiple SCT specimens. From the Fig. 3 a slope change is revealed at 95 MPa $m^{1/2}$ for parent metal and 85 MPa $m^{1/2}$ for weldments. There is a steady increase in SIF after this point. The SIF for weldments for all crack sizes is about 95% of that for parent metal. One more inference is that for a particular $B = 0.0075$ m of the material, there is stable crack growth after a K value of 95 MPa $m^{1/2}$ for parent metal and after 85 MPa $m^{1/2}$ for weldments. Incidentally these K values correspond to the KIC of the material for parent metal and weldment respectively. It has been shown [7] that R-curve characteristics of 18 Ni 1800 MPa maraging steel plates (parent metal) of 0.0075 m thickness yielded slope change at 95 MPa $m^{1/2}$, thus confirming that maraging steel sets up good

TABLE IV 18 Ni 1800 MPa Maraging steel; welded; $W = 0.030$ m

Sl. No.	Crack size, $a \times 2c$ (m)	σ_r (MPa)	σ_{SCTS} (MPa)
1.	0	1720 (UTS)	–
2.	0.00095 × 0.0027	1703	1718
3.	0.0012 × 0.0029	1732	1754
4.	0.0019 × 0.004	1724	1769
5.	0.0019 × 0.0042	1689	1737
6.	0.0019 × 0.0042	1726	1775
7.	0.0018 × 0.0043	1721	1768
8.	0.0021 × 0.0049	1703	1766
9.	0.0022 × 0.005	1690	1756
10.	0.0022 × 0.0052	1662	1729
11.	0.0022 × 0.0052	1713	1783
12.	0.0025 × 0.0056	1668	1750
13.	0.0023 × 0.0059	1693	1775
14.	0.0028 × 0.006	1647	1747

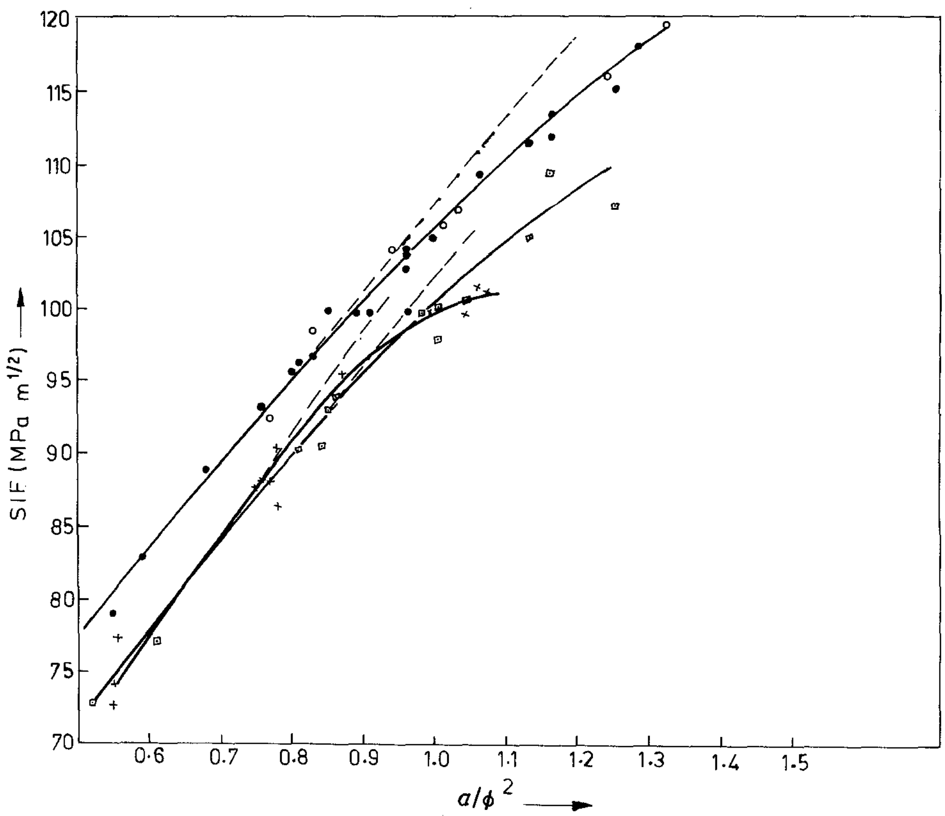

Figure 3 SIF against a/ϕ^2 plot for parent metal and weldments. (●) parent metal LT, (○) parent metal TL, (x) autoweld 15 mm wide, (⊡) auto weld 30 mm wide.

resistance to crack growth and exhibits stable crack growth before failure. The fracture surfaces of CT specimens used for the *R*-curve studies showed about 50% shear slip ahead of crack tip.

3.3. Surface crack tensile strength, σ_{SCTS}

The presence of a sharp notch alters the stress distribution to provide a stress concentration at the tip of the notch. The notch strength-ratio [8] will show whether or not a material is notch sensitive and prone to brittle fracture in the presence of the stress concentration. In the present experiments the surface crack is considered to be a notch in the material and surface crack tensile strength σ_{SCTS} is defined as, UTL of SCT specimen/Total area − crack area. The values of σ_{SCTS} for parent metal and weldments are given in the last column of Tables I to IV. The lowest values of $\sigma_{SCTS/UTS}$ ratio is observed to be 1.02 for parent metal and 1.005 for weldments, thus indicating that the material is not prone to brittle fracture. Another inference is that the strain hardening effect in the material is not significant.

3.4. Flaw detectability

The relevance of σ_r data generated here for 18 Ni 1800 MPa grade maraging steel for non-destructive testing (NDT) method is very significant since for fracture based design approach detectability of flaws with 99% probability and 95% confidence level is essential. For a maraging steel rocket motor case of particular thickness the critical flaw size is known from KIC of the material and proof pressure to which fabricated chamber will be subjected to. The σ_r data on weldments have shown that the reduction in strength from UTS to one with 0.0028 × 0.006 m flaw is only 5%. Having fixed the design stress, this data gives good scope for the quality and reliability inspector to choose a suitable NDT technique like ultrasonics with which it is possible to detect flaws in the range up to 0.0028 = 0.006 m size to ensure high reliability for the mission.

4. Conclusions

(1) For crack size of 0.001 × 0.003 m the residual strength in parent metal is 1850 and 1800 MPa for LT and TL directions respectively. In the case of weldments the residual strength for the 0.001 × 0.003 m crack size is 1710 MPa for both 0.015 and 0.03 m wide panel specimens. This value is about 95% of the parent metal residual strength.

(2) The reduction in residual strength (0.007 m crack length) in parent material is of the order of 7% when compared with UTS of the material. Similarly in 0.015 m wide panel weldment also the reduction in residual strength (0.0068 m crack length) is of the order of 9% in comparison with the UTS of weldment.

(3) For 0.03 m wide autowelded panel the reduction in residual strength value when compared with the UTS of the weldment is only 5% for the maximum crack length, 0.006 m. Variation in residual strength from minimum crack size (0.00095 × 0.0027 m) to maximum crack size (0.0028 × 0.006 m) lie within 5% of the UTS of the weldment.

(4) The general requirement of specimen width, W(Min) ⩾ 5 × 2c, enables us to provide a valid simulation of infinite plate conditions. But it has been observed [9] that specimens of some what shorter or narrower width may provide equally valid

solutions. In the present experiments also the residual strength values obtained from the 0.015 m wide auto welded specimen for the larger crack dimensions (0.00215 × 0.00535 m) and those obtained from 0.03 m wide autowelded specimen for similar crack dimensions (0.0022 × 0.0052 m) are very much comparable.

(5) SIF data shows that for thickness chosen for the present study, the material sets up good resistance and stable crack growth before failure.

(6) $\sigma_{SCTS/UTS}$ ratio shows the material to be marginally notch ductile.

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