MEAN STRESS AND NOTCH EFFECT IN HCF EXPERIMENTS ON ALLOY 617 BETWEEN 600 AND 950 °C

H. Diehl, Hochtemperatur-Reaktorbau GmbH, Mannheim, FRG

C. M. Sonsino, Fraunhofer-Institut für Betriebsfestigkeit LBF, Darmstadt, FRG

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1. Introduction

The heat exchanger tubing in a high temperature gas cooled reactor is subjected both to a static loading due to the inner pressure and to a high frequency loading, superimposed on this, due to fluid flow effects. In order to investigate the behaviour of the material under conditions similar to those expected in service, HCF experiments at various mean stresses and stress rupture tests were carried out on smooth, on notched and on welded samples of Alloy 617 (NiCr23Co12Mo) at temperatures between 600 °C and 1000 °C.

The abrupt transition from the solidified material of the welding seam to the wrought base material in Alloy 617 weldments may be understood as an internal notch of a structure. This effect is to be compared with the effect of a circumferential notch in cylindrical specimens of the base material. Also the notched specimens cover effects of rough unmachined surfaces.

It is intended to give a statement on the influence of mean stresses, weldments and notches on the long-term behaviour of the component by trend curve evaluation.

Alloy 617 is preferably applied in the temperature range 800 to 1000 °C, because of its good high-temperature creep-rupture strength. Nevertheless investigations at 600 °C were performed to determine the extent of notch-weakening tendencies which are found in stress-rupture tests at 550 to 650 °C for several high-temperature superalloys.

2. Abbreviations

Sa : stress amplitude of smooth specimens
Sak : stress amplitude of notched specimens
Saw : stress amplitude of welded specimens
Sm : mean stress of smooth specimens
Smk : mean stress of notched specimens
Smw : mean stress of welded specimens
Su = Sm-Sa : minimum stress
So = Sm+Sa : maximum stress
S = Su/So : mean stress parameter
A = Sa/Sm : mean stress parameter
Nf : Cycles to failure
Rmt : stress rupture strength of smooth specimens
Rmtk : stress rupture strength of notched specimens
Rmts : stress rupture strength of welded specimens
tr : time to rupture
Kt : stress concentration factor

3. Test material

Alloy 617 (nickel base alloy)
German standard designation : NiCr23Co12Mo

Standard No. 2.4663
Product form: Plate, 21 mm thick
Heat treatment: solution annealing
Grain size: ASTM 2 - 4
Welding process: MIG impuls (root weldment: TIG)
Welding material: filler metall Alloy 617
Shape of welding seam : X shape

4. Experimental parameters

Creep rupture tests were performed at 600, 700, 800, 900 and 1000 °C with smooth and notched cylindrical specimens. The welded specimens were taken from the plate with the welding seam perpendicular to the specimen axis. The weld toes were completely removed so that the unnotched specimens consisted of the welded, the heat affected and the not affected material zones. The diameters were 6 - 10 mm. The time to rupture has reached about 55.000 h with specimens still on test.

The HCF tests were performed at test temperatures of 600, 850 and 950 °C. The test equipment used was a high-frequency load-controlled pulsator, the test frequency was 150 Hz. The specimens used corresponded to those of the creep-rupture tests. The diameter of smooth and welded specimens was 6 mm; the surface was polished. The outer diameter of the notched specimens was 8 mm, the inner diameter 6 mm, the notch radius 0.5 mm. The stress concentration factor Kt was 2.5. The tests were conducted under appliction of mean stresses Sm = 0 (S = -1), Sm = Sa (S = 1) and Sm = 5/3 Sa (S = 0.25).

5. Experimental results

5.1 Creep-rupture tests

The isothermal stress-rupture curves are plotted in Fig. 1 with the experimental values for smooth specimens. Fig. 2 shows that at 600 °C test temperature notch weakening occurs at long testing times. This is connected with a drop in rupture elongation to low values. The close approach of the stress-rupture curves of notched and smooth specimens at 950 °C is due to decreasing notch strengthening on the account of high creep ductility.

5.2 HCF tests

Test results of the HCF tests for smooth specimens are given as an example in Fig. 3 for S = 0 (Sa = Sm) at 600, 850 and 950 °C. The corresponding values for notched specimens (Fig. 4) are considerably lower in the range of low Nf-values compared with those for smooth specimens. The trend curves demonstrate that at high temperatures in the long-term range the curves are expected to intersect.

6. Evaluation and discussion of results

6.1 Notch effect at mean stress Sm(k) = 0 (S = -1)

The notch-strength ratio Sak/Sa is very similar at 850 and at 950 °C and shows an increase with time (Fig. 5). For short testing times the curves approach to Sak/Sa = 1/Kt = 0.4. Though the material is very ductile at such high temperatures, the peak stress in the notched cross section of the specimens dominates the failure process. At longer testing times this effect becomes weaker, because the peak stress is apparently reduced by plastic deformation processes (perhaps relaxation) during cycling, thus the notch becomes less detrimental.

6.2 Notch effect at mean stress Sm(k) = Sa(k) (S = 0)

The notch-strength ratio Sak/Sa for the test temperatures 600, 850 and 950 °C is about 0.6 to 0.8 at short testing times (Fig. 6). At 600 °C it decreases slightly with increasing testing time; the notch weakening increases because of the time-dependent embrittling tendencies of the material at this temperature which makes the material more sensitive to peak stress damage under static and dynamic load.

At 850 and 950 °C the notch-strength ratio Sak/Sa raises strongly with increasing time, the notch weakening decreases. The peak stress is reduced by plastic and creep deformation as well as by relaxation under the mean stress applied and by HCF effects (as can be seen in Fig. 5). Therefore, the detrimental influence of peak stress decreases with time.

The notch strengthening which occurs at 850 and 950 °C under creep-rupture conditions (Fig. 7) controls the material behaviour under dynamic loading at S = 0 to an increasing extent.In the long term the notched specimens exhibit a longer life than the smooth specimens due to the restraint imposed by the multiaxial stress condition in the notched cross section, which limits the extent of creep deformation under stress-rupture conditions as well as under high-cyclic loading in tension.

At 950 °C this effect seems to be more pronounced at HCF load (S = 0, Sa = Sm; Fig. 6) than under stress rupture conditions (S = 1, Sa = 0; Fig. 7). This phenomenon may be explained by dynamic strain hardening effects under the very high strain rate of the fatigue tests. There is not sufficient time for the material to recover during the half cycle with decreasing load after the strain hardening period during the half cycle with increasing load. So the creep resistance is evidently increased as can be seen from Fig. 15 and the notch strengthening effect is more pronounced than in notched specimens under creep.

6.3 Notch effect under stress-rupture conditions (Sa = 0, S = 1)

As expected the notch strength ratio Rmtk/Rmt at 600 °C becomes lower than 1 at times beyond 10^4 h (Fig. 7). At 850 and 950 °C the strongly pronounced notch strengthening at short times is diminished with time, but the ratio always is greater than 1. This applies also for sharper notches (Kt = 4 - 4.5). It means that premature failure will not occur under the influence of notches.

In the long term the poor notch-strengthening behaviour at 900-1000 °C seems to be caused by the rather low creep resistance and by high creep deformation even in the notched cross section. The notch radius increases while the restraint of the notch decreases. Thus the behaviour of notched specimens becomes similar to that of smooth specimens.

6.4 Boundary lines between notch strengthening and notch weakening behaviour (Sak/Sa = 1)

The data in Fig. 5 to 7 show the dependence of the notch-strength ratio Sak/Sa on the mean stress parameters S (Su/So) and A (Sa/Sm). The values for the condition Sak/Sa = 1 can be obtained from the plots Sak/Sa over S (Fig. 8-10). It can be seen in Fig. 11 that at temperatures above approx. 750 °C an increasing proportion of stress amplitude Sa can be tolerated with increasing load time and temperature without having to expect notch sensitivity . The trend curves show for example that at load times beyond 10^5 h and at temperatures above 750 °C the stress amplitude Sa may be greater than the mean stress Sm (i. e. $S < 0$; $Sa/Sm > 1$) without any negative influence from the notch.

At temperatures of about 600 °C the mean stress parameter S increases to 1 (Fig. 12). This means a notch sensitivity in the long-term range under stress-rupture conditions as well as under any fatigue conditions.

6.5 Sa-Sm diagrams

The notch sensitivity for all Sm-conditions at 600 °C in the long-term range (10^5 h) is confirmed in the Sa-Sm diagram (Fig. 13), which is incomplete for this temperature because of some lack of data. But at least it can be demonstrated that there is an intersection of the curves for notched and smooth specimens at short times (10 h), whereas there is none for longer times (10^5 h). Thus the point of intersection moves towards S = 1 as a function of time . On the other hand, the point of intersection in the corresponding diagram for 950 °C is shifted from a higher S-value at 10 h to a lower S-value at 10^4 h (Fig. 14). This means a trend to notch-strengthening with increasing testing time.

The curves for 10^4 h in Fig. 14, both for smooth and notched specimens, are bent backward with increasing Sm in their lower part. This means that in the long-term range in both cases service life under constant load is increased by a superimposed HCF load. This behaviour has been verified by the experimental values for smooth specimens at 950 °C (Fig. 15). In this figure the Sm curve for S = 0 (Sa = Sm) intersects with the stress rupture curve. The uncertainty of the trend curve at long times may only change the extent of this effect, which was found for other high temperature materials by other authors, too /1/.

6.6 Behaviour of welded joint specimens

The HCF behaviour of the welded joint specimens is - compared with the behaviour of notched specimens - similar to that of the base material as can be seen in the Sa-Sm diagram for 950 °C (Fig. 16) and in the Sak-Nf diagram (Fig. 3, 850 °C, S = 0). The Saw/Sa ratio at 850 °C is close to 1 for the whole range of S = -1 to S = +1 (Fig. 17).

The rupture predominantly occurred in the welding seam in the fatigue tests as well as in the creep-rupture tests and only in some cases in the base material.

7. Summary and conclusions

- Creep-rupture tests up to 55000 h and HCF tests up to 360 h testing time in the temperature range 600 to 1000 °C on specimens of Alloy 617 are the basis for developing time and temperature dependent trends to give a statement on the long term behaviour of the material with respect to its application for HTR-heat exchangers regarding the influence of mean stresses, notches and weldments.

- The behaviour of specimens of the weldment is similar to that of the base material. In contrary to this, the behaviour of notched specimens (Kt = 2,5) is very different. Thus the external notch of the base material has a stronger effect than the internal notch caused by the abrupt transition from welding material to the wrought base material. Therefore, the results on the notched specimens cover the influences of unmachined rough surfaces of the base material and the welded joint (e.g. weld toes).

- The experiments were performed at a load frequency of 150 Hz. High-temperature HCF tests at frequencies from 40 to 174 Hz /2/ which cover the frequency range expected for heat-exchanger tubings, showed no influence of the frequency on the material behaviour. Thus the results and conclusions of the investigations presented in this paper can be applied more generally.

- The trend to slightly increasing notch sensitivity with increasing testing time at 600 °C does not seem important for the application of Alloy 617 in high temperature components. The service temperature of these components are between 800 and 1000 °C. In this temperature range the trend curves show a notch-strengthening behaviour at long times under load (more than about 10^4 - 10^5 h), even if the stress amplitude matches the mean stress. This behaviour is apparently caused by dynamic strain hardening effects as well as by a high restraint of the notch. Under operating conditions the stress amplitudes in heat exchanger tubings which are superimposed to the stresses from the internal pressure, are small compared with these static stresses (Sa < Sm, S > 0). Therefore, no detrimental effect is to be expected on the tubings from the high frequency dynamic loads.

8. References

/1/ Kloos, K. H; Jahr, O.: Hochtemperatur-Schwingfestigkeitseigenschaften artgleicher Schmiede- und Feingußwerkstoffe unter besonderer Berücksichtigung der Korngröße. Forschungsberichte Verbrennungskraftmaschinen Heft 268 (1980) der Forschungsvereinigung Verbrennungskraftmaschinen, Frankfurt/Main, FRG

/2/ Wiegand H., Kloos K. H., Jahr, O.: Der Einfluß ruhender und wechselnder Beanspruchungen auf die langzeitigen Festigkeitseigenschaften einiger hochwarmfester Werkstoffe. Forschungsberichte Verbrennungskraftmaschinen Heft 177 (1975) der Forschungsvereinigung Verbrennungskraftmaschinen, Frankfurt/Main, FRG

9. Acknowledgement

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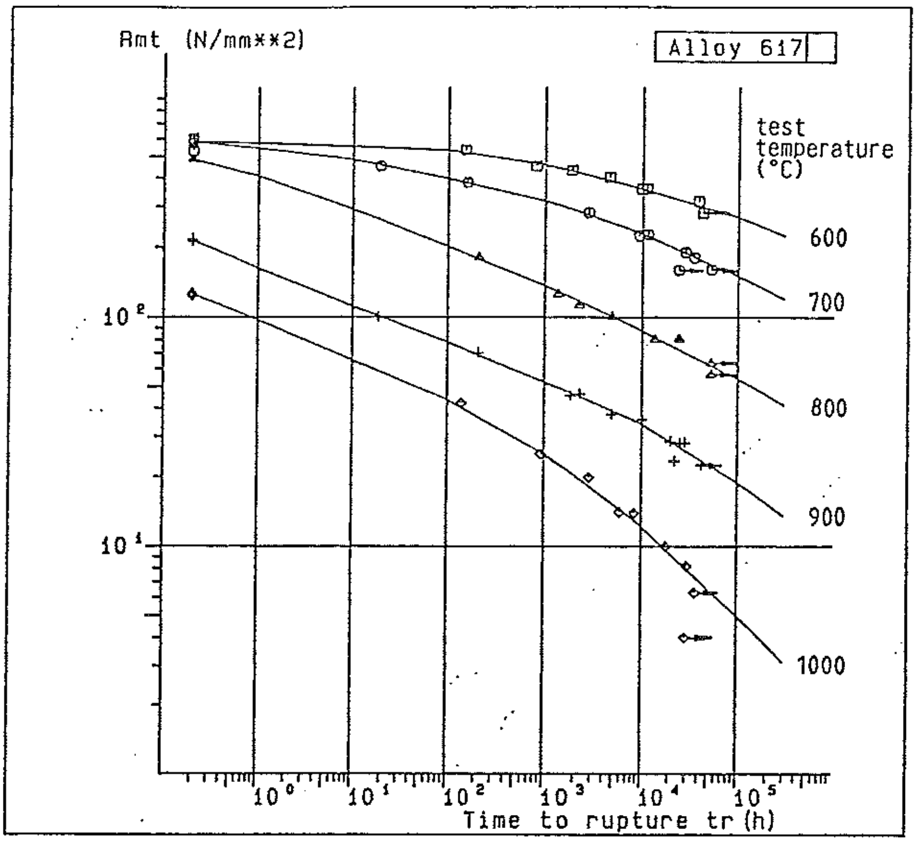

Fig. 1 Results of creep-rupture tests on smooth specimens

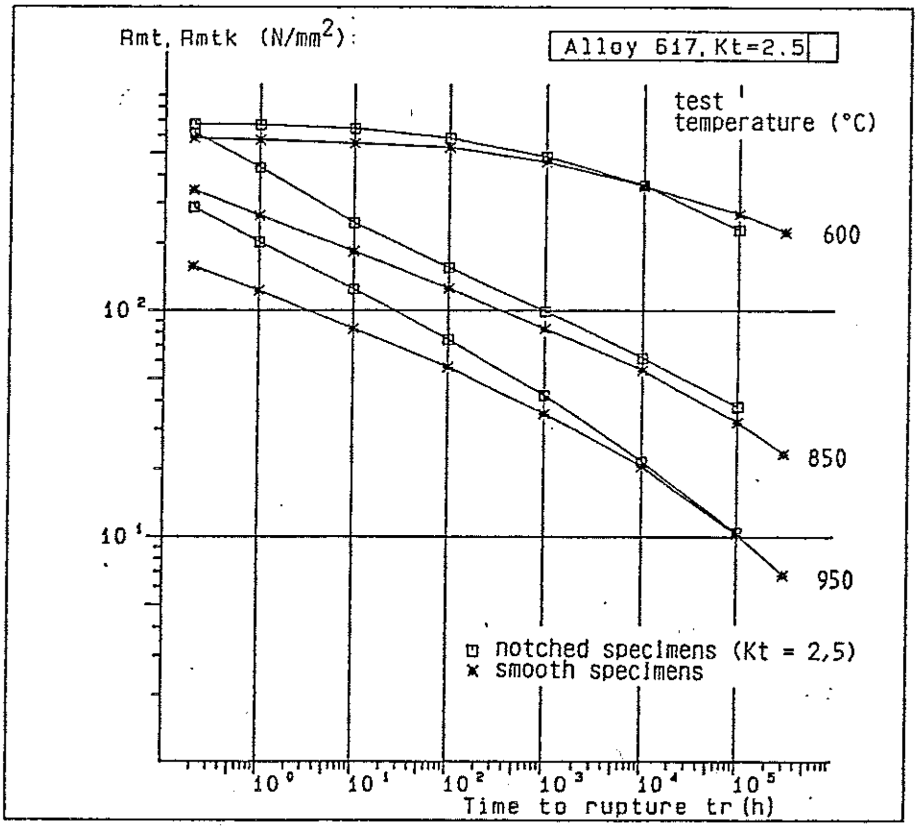

Fig. 2 Isothermal stress-rupture curves for notched and smooth specimens

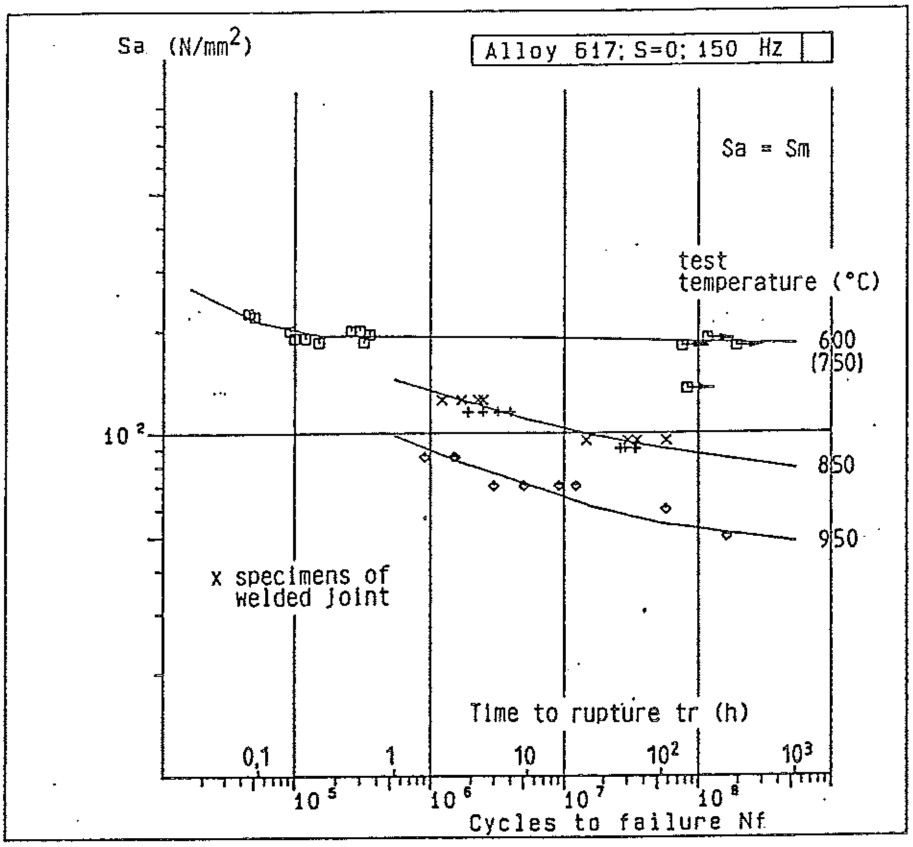

Fig. 3 Results of HCF tests on smooth specimens at 600, 850 and 950 °C (S = 0, Sa = Sm)

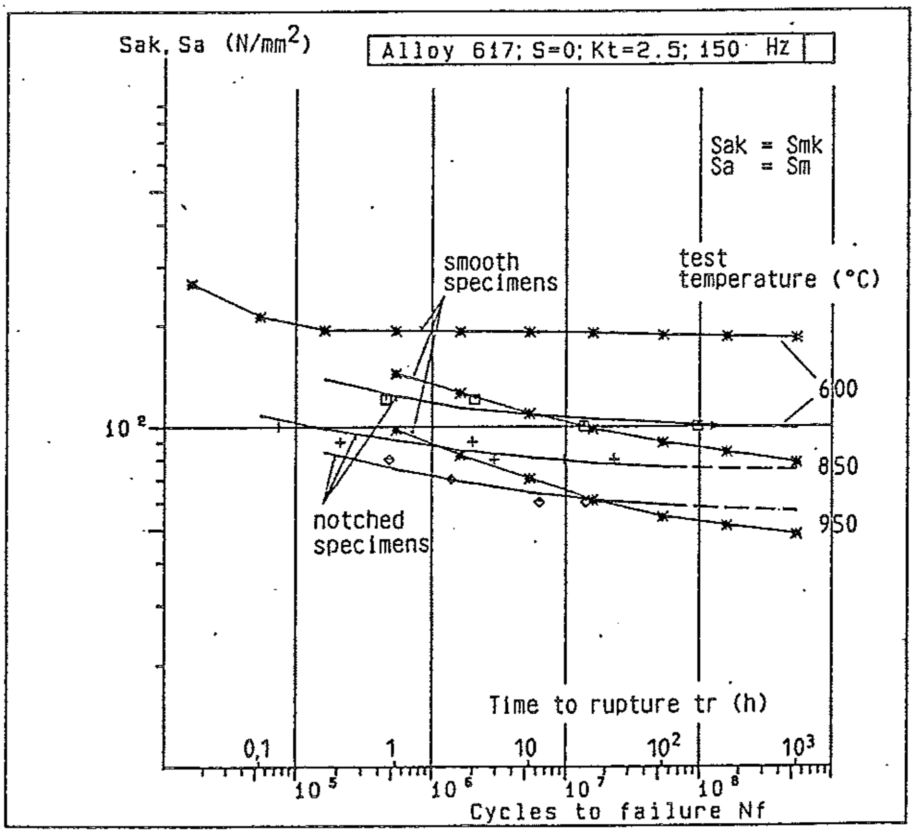

Fig. 4 Results of HCF tests on notched specimens at 600, 850 and 950 °C (S = 0, Sa = Sm)

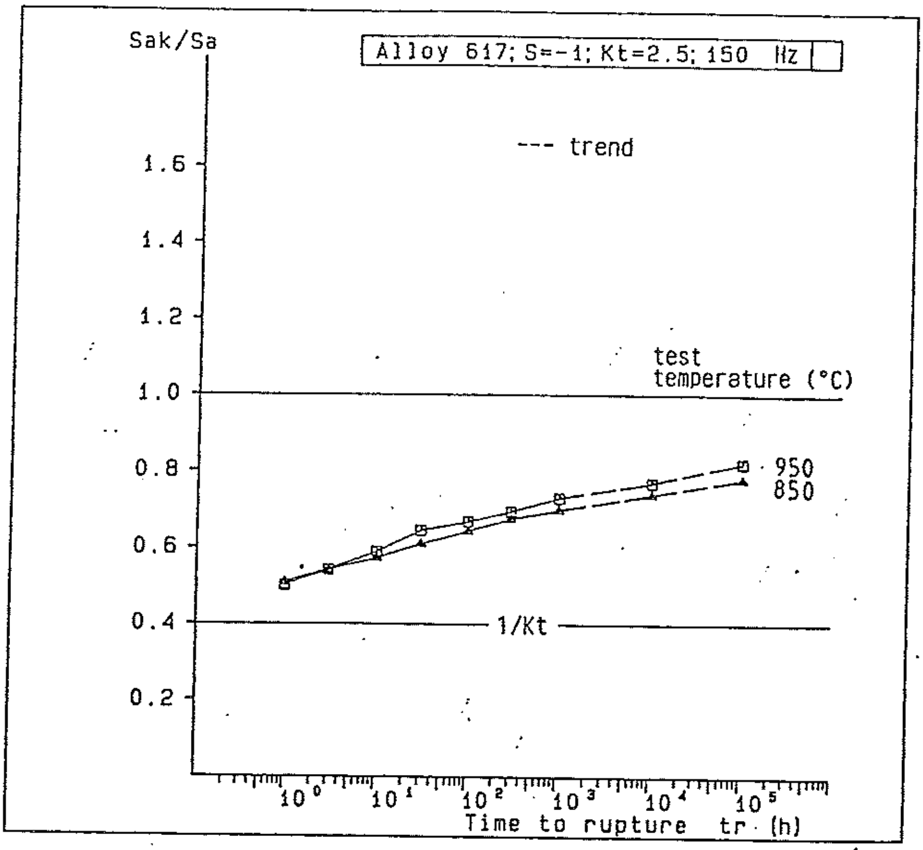

Fig. 5 Notch-strength ratio Sak/Sa as a function of time to rupture tr for S = -1 (Sm = 0).

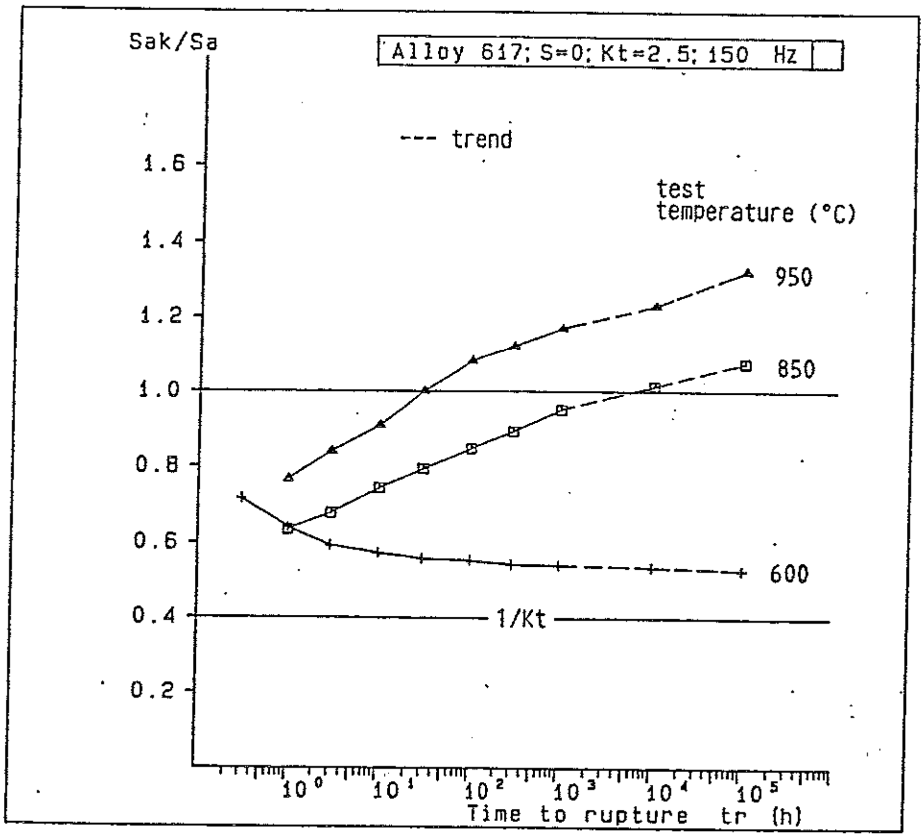

Fig. 6 Notch-strength ratio Sak/Sa as a function of time to rupture tr for S = 0 (Sa = Sm)

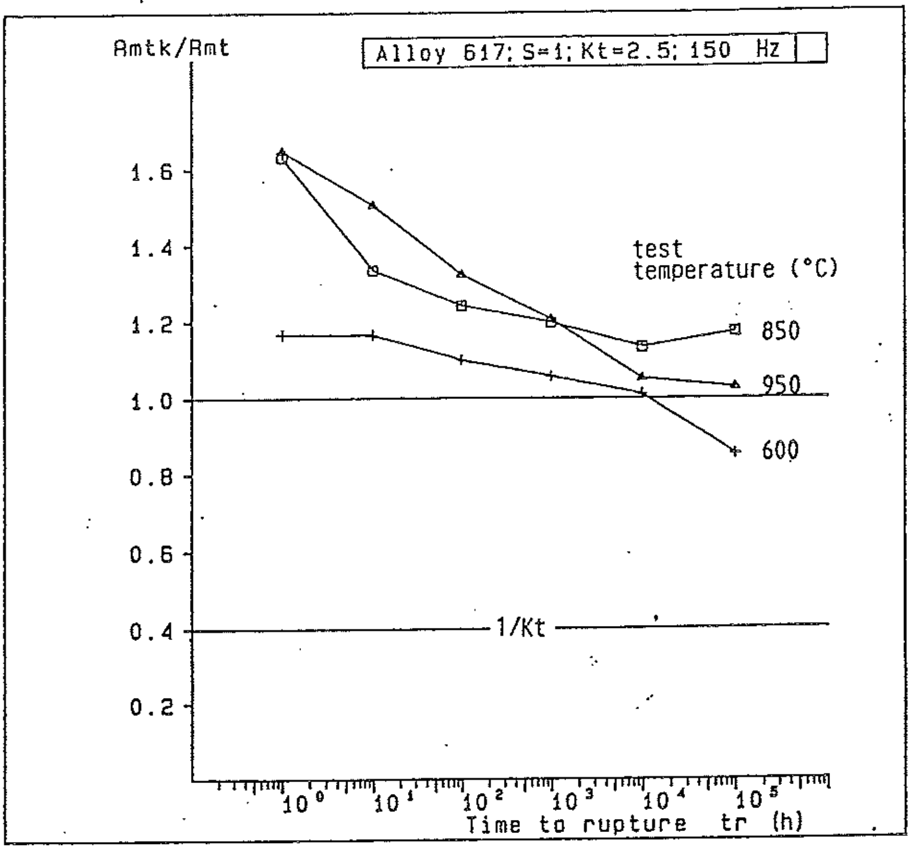

Fig. 7 Notch-strength ratio Rmtk/Rmt as a function of time to rupture tr (S = 1, Sa = 0)

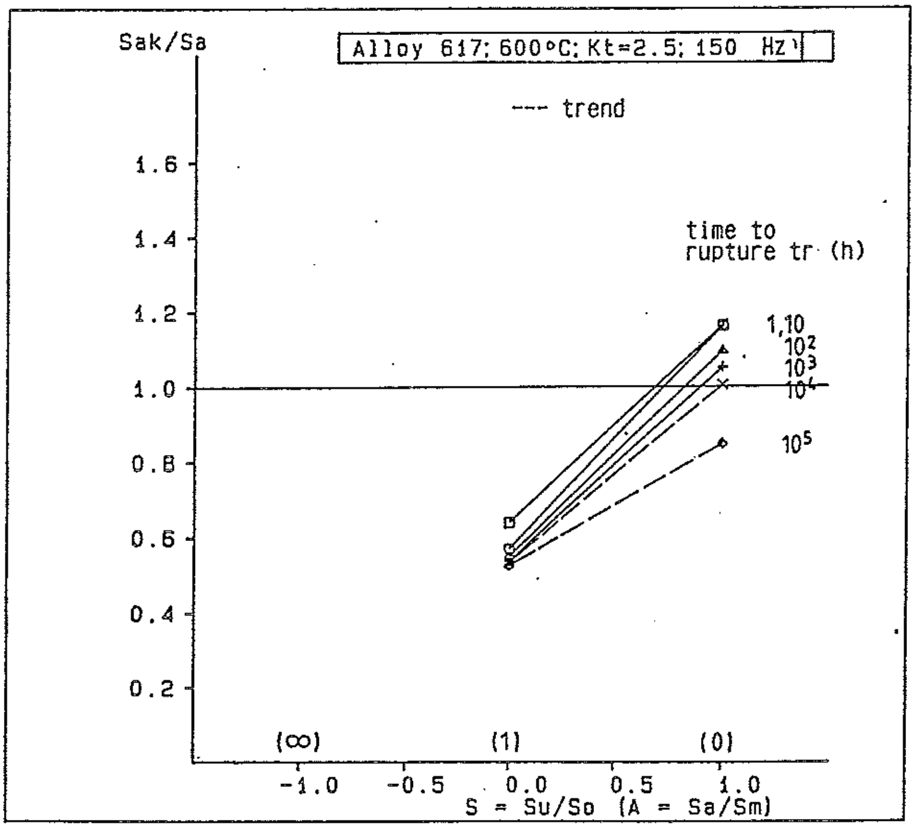

Fig. 8 Notch-strength ratio Sak/Sa at 600 °C as a function of the mean-stress parameter S (A)

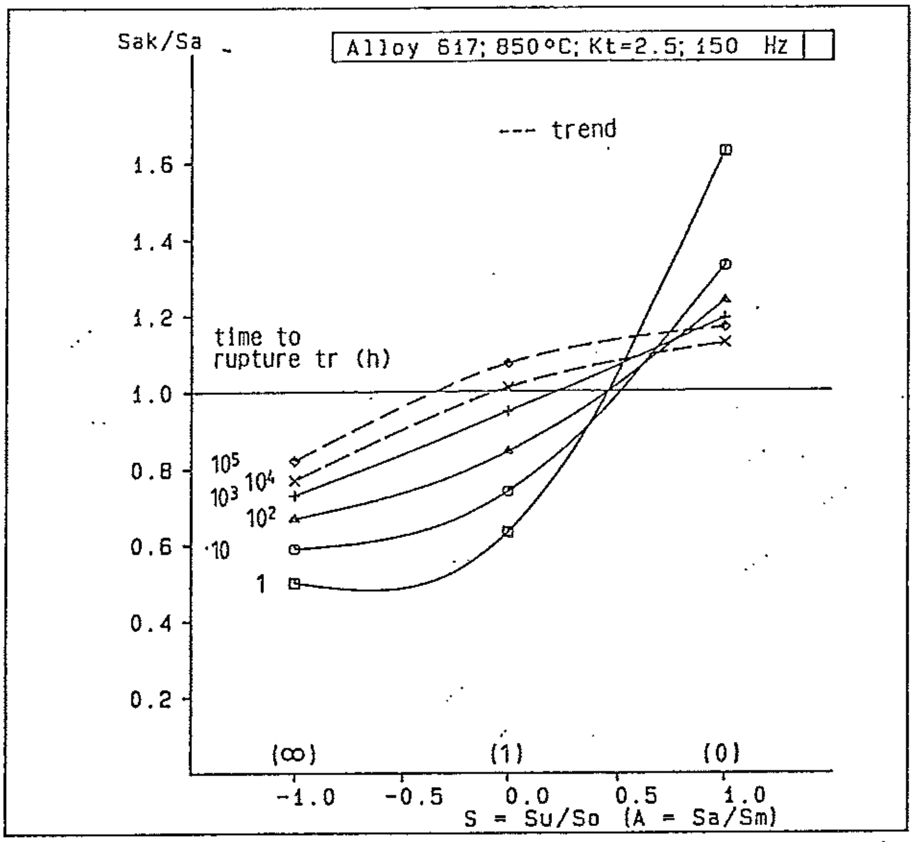

Fig. 9 Notch-strength ratio Sak/Sa at 850 °C as a function of the mean-stress parameter S (A)

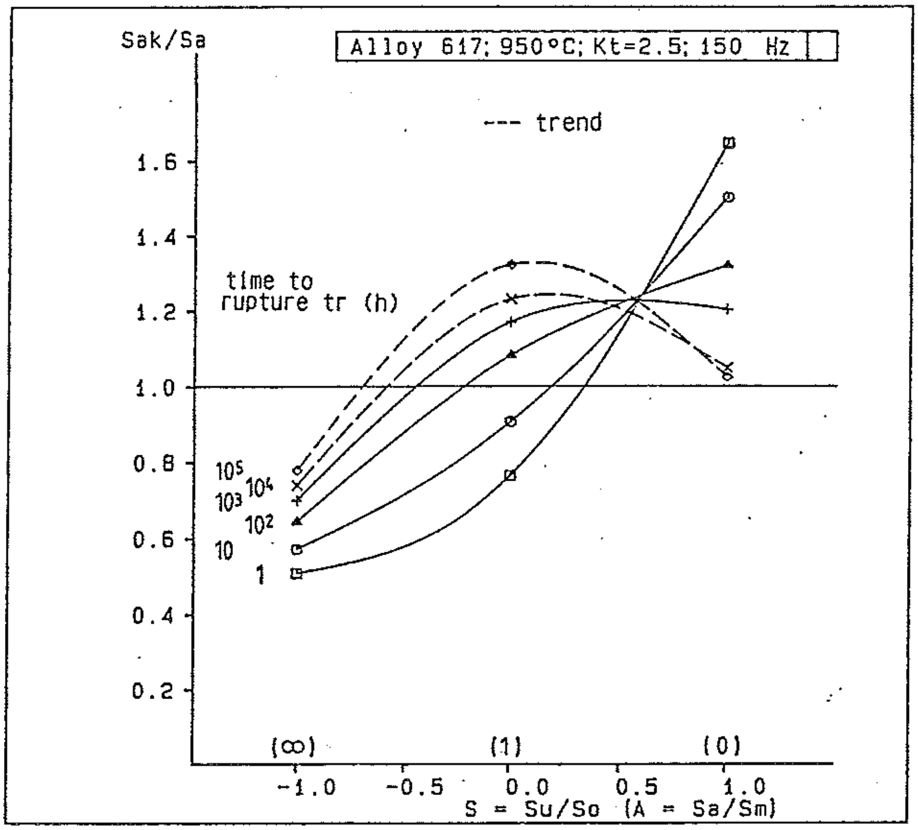

Fig. 10 Notch-strength ratio Sak/Sa at 950 °C as a function of the mean-stress parameter S (A)

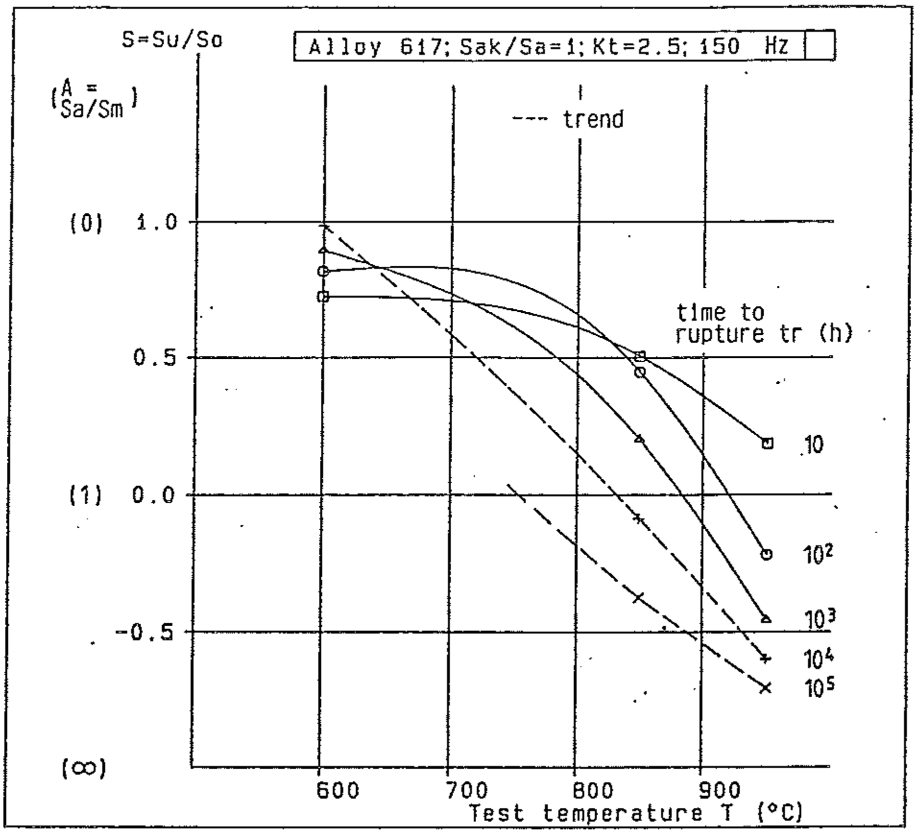

Fig. 11 Mean stress parameter S (A) at Sak/Sa = 1 as a function of test temperature T

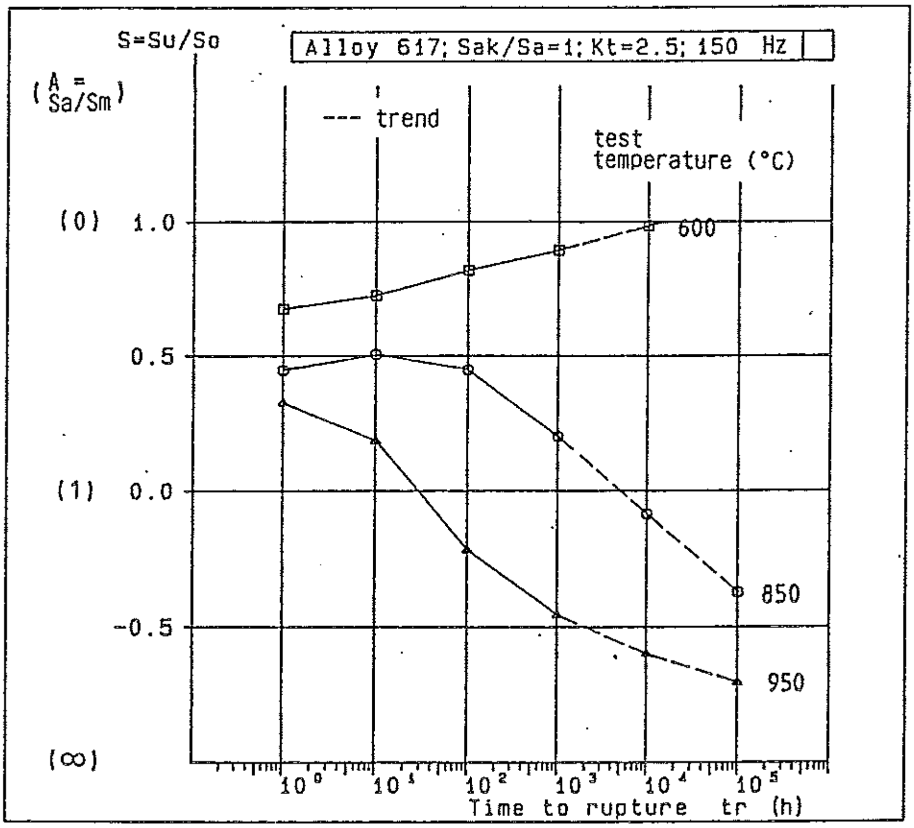

Fig. 12 Mean stress parameter S (A) at Sak/Sa = 1 as a function of time to rupture tr

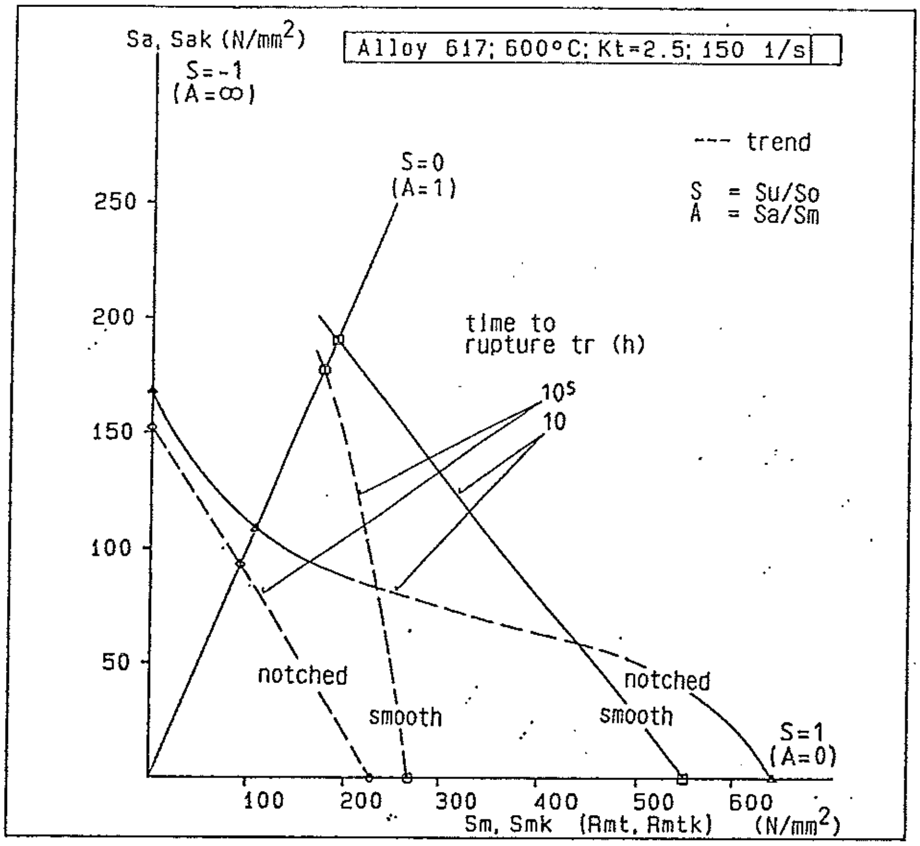

Fig. 13 Sa-Sm diagram for smooth and notched specimens at 600 °C

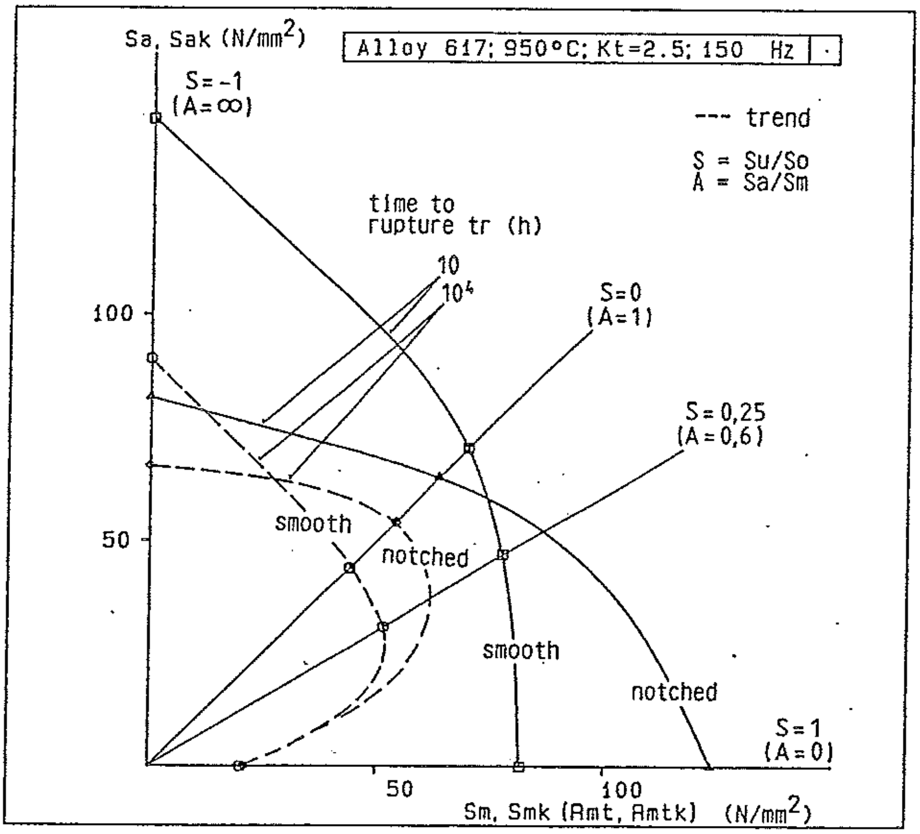

Fig. 14 Sa-Sm diagram for smooth and notched specimens at 950 °C

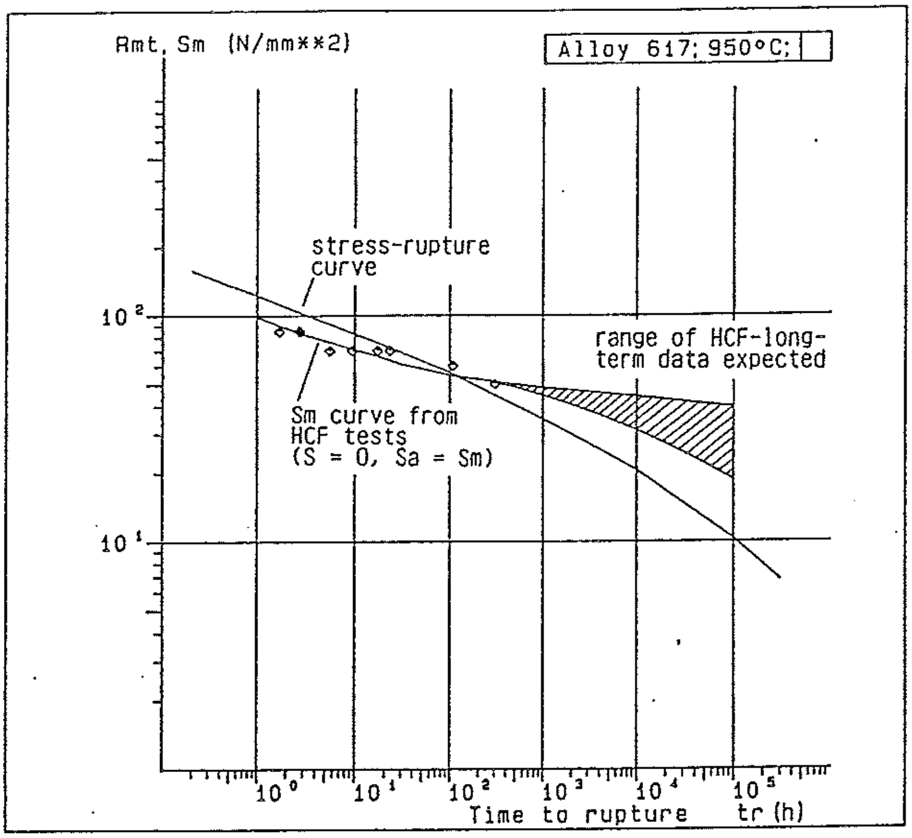

Fig. 15 Stress-rupture curve and mean-stress curve (Sm) from HCF tests at 950 °C (Sa = Sm)

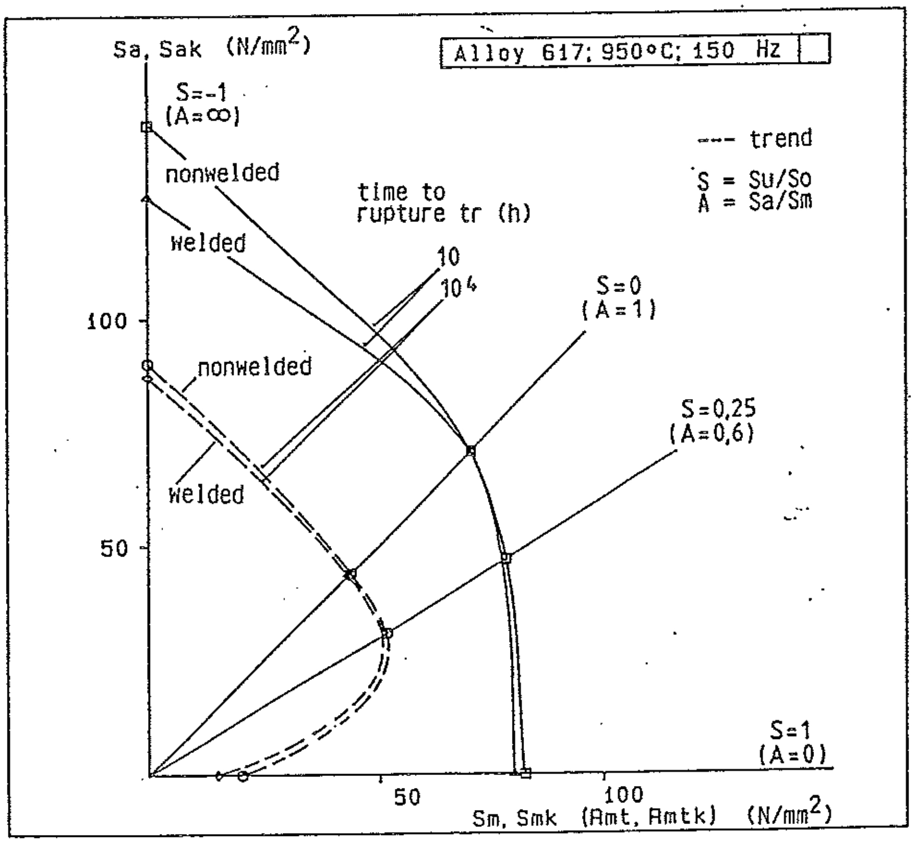

Fig. 16 Sa-Sm diagram for nonwelded and welded specimens at 950 °C

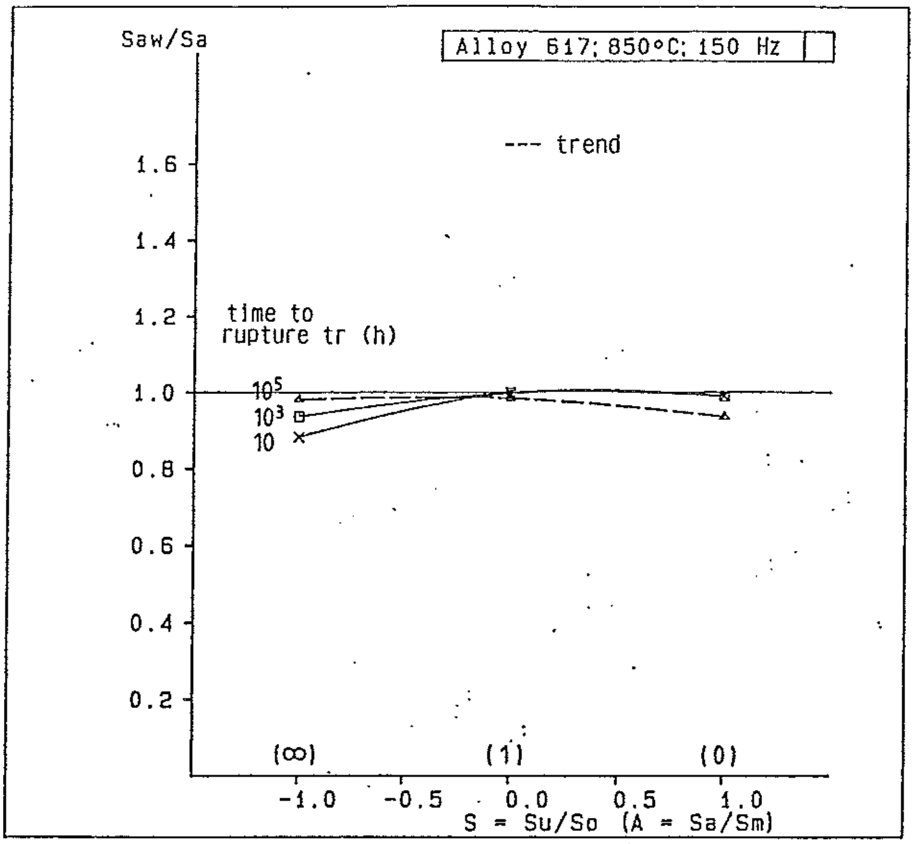

Fig. 17 Strength ratio Saw/Sa for welded and nonwelded specimens as a function of the mean-stress parameter S (A)