HIGH TEMPERATURE LOW CYCLE FATIGUE DAMAGE ANALYSIS OF WELDED STAINLESS STEEL TUBULAR ELEMENTS

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Summary

This paper presents the results of a damage analysis of welded tubular specimens subjected to low cycle high temperature fatigue.

Flanged and TIG butt welded tubular specimens in AISI 304 stainless steel have been cycled at 650°C between fixed strain limits.

The failure has been localized in the central butt weld, where there is a marked concentration of plastic strain owing to the differences in the $\sigma - \varepsilon$ response of the base and weld metal and of the coarse grain heat affected zone.

Metallographic analysis of the zone around the failure has shown that the cracks nucleate at grain boundaries at the inner surface of the tubes. The rupture occurs in the heat affected zone and procedes transgranularly at the interface between heat affected zone and weld metal.

Material and test parameters are reported and results of metallographic analysis are presented and discussed with the aid of mechanical properties of small samples drawn from different zones.

1. Introduction

The influence of weldments in structures subjected to high temperature low cycle fatigue represents a major challenge for a proper design of high temperature reactor components.

An experimental study of the behaviour of simple welded tubular structures in austenitic stainless steels has been carried out at the Istituto di Impianti Nucleari of the University of Pisa with the sponsorship of C.N.E.N..

During these experiments, model structures in AISI 304 stainless steel have been cycled between fixed total strain limits in axial loading at 650°C. The test parameters are presented in Table I, the design of the specimens is given in Fig. 1.a.

All the weldments have been performed with an automated TIG apparatus, without filler metal.

As reported at the 4th SMiRT Conference /1/ the specimens show a marked life reduction if compared with smooth small size specimens in AISI 304 subjected to the same total strain range at 650°C, as reported in literature.

The life reduction of the welded specimens (factor of 10 ÷ 50 on life) may be due to the following main causes:

- plastic strain concentration in the weld metal (WM) and in the heat effected zone (HAZ);
- lower fatigue properties of the WM and HAZ;
- surface roughness effects.

The first cause has been explored with the aid of finite element non linear analysis, reported elsewhere /2/, and may be qualitatively evaluated taking into account that the yield strenght of the coarse grain HAZ, calculated by means of the Hall-Petch equation, is about 10% inferior than the yield strenght of the fine grain base material (130 MPa). It may be appreciated that when the HAZ yields, the base material is about 15 MPa below its yield point.

The large effect of this cause on life reduction may also be appreciated by the fact that specimens annealed after welding, characterized by a much more homogeneous metallurgical structure throughout, show a fatigue life about two fold longer than the specimens which have not been subjected to an anneal heat treatment (Fig. 2).

With regard to the other causes of life reduction, a lower high temperature fatigue resistance of WM and HAZ has been observed by several researchers /3,4,5/.

An experimental study to ascertain this behaviour is in its first phase of development.

Surface roughness effects on fatigue life are also well known even in low cycle rupture cases /6/.

2. Experimental part

Material characterization and metallurgical analysis related with the above indicated high temperature low cycle fatigue experiments has been carried out at Material Science Division of Joint Research Centre at Ispra.

The chemical composition of the base material is given in Table I. The same table presents the results of room and high temperature monotonic testing.

Surface finish measurement have been performed either before and after the tests. The mean value of the virgin material is about 1.5 μm R.M.S.. After the tests the roughness at the inner surface of the tubes reaches a value about 4 μm R.M.S., while at the outer surface, which is polished before each test for residual mean strain measurement purposes, the roughness is about 1.5 μm R.M.S. at rupture.

3. Metallographic analysis

After low-cycle fatigue tests, the tubular elements were sectioned to show any evidence of internal or superficial damage and of other microstructural modifications. The sections planes were both transverse and longitudinal with respect to the tube axis.

The analysis carried out with standard metallographic techniques did reveal homogeneous response of the tubes which experienced different cycles number prior to rupture. The microstructure through the thickness of the tubes in the parent metal is typical of a stainless steel heat treated in the temperature range in which carbide precipitation occurs. In the parent metal the average grain size is comprised between 50 ÷ 60 μm while in the heat affected zone the grain size ranges between 120 and 500 μm. The HAZ, the WM and the parent metal did not show any internal crack or void. A large number of cracks were observed in the inner surface of the tubes in the parent metal, in the HAZ and in the WM whereas in the outer surface very few cracks were observed only in the middle of the WM. A large amount of slip is also observed on the inner surface giving rise to the formation of "orange peeling". The outer surface shows sign of recrystallization due to the mechanical polishing carried out before the low cycle fatigue tests. Microcracks observed on the inner surface nucleate at grain boundary at the very beginning of the fatigue life as they have been observed after a few cycles. Propagation of the microcracks occurs also at the grain boundaries but only for a depth of 20÷30 μm depending on the local grain size. Afterwards the cracks progress in a transgranular propagation mode in the HAZ or/and in the WM. The rupture occurs always in these zones: this fact confirmates the strain concentration effect of this low yield microstructure and may be related to the apparent lack of ductility of the HAZ.

A typical example is reported in Fig. 4 which shows the propagation of a circumferential crack starting in the HAZ and continuing in the WM. The five serial section have been taken longitudinally at an angle of roughly 10° each other.

With the aim at characterizing the stress-strain behaviour of different zones, short time tensile tests at 20°C and at 650°C were carried out on small specimens machined from tubes in different conditions, i.e., as received (A), solution annealed and fatigue tested for 943 cycles with a $\Delta\varepsilon$=0.46 at 650°C (B), fatigue tested for 70 cycles with $\Delta\varepsilon$=0.50% (C).

As indicated in Fig. 1(b) the specimens were machined across the weld (a), along the weld (b) and in the parent metal in longitudinal (c) and circumferential (d) direction.

Both the ultimate tensile strength and the yield strength show little variations due to the location of the specimens or to the prior treatment of the tubes. The ductility, measured as the total elongation to rupture, on the contrary varies in quite a marked way as shown in Fig. 3. It may be argued that the low rupture elongation shown by specimens type (a) is due either to strain concentration in the HAZ as well as to a reduced ductility of this zone.

5. Conclusions

Reproducing high temperature low cycle fatigue conditions on a simple welded structural component in AISI 304 S.S. by means of continuous cycling between fixed total strain limits has shown a marked reduction of failure life if compared with the life of smooth small size specimens subjected to the same nominal total strain range.

It has been ascertained that one of the main causes fo the behaviour is due to highly localized plastic strain concentration.

Residual mean strain measurements, non linear finite element analysis and metallographic evidence all confirmate this behaviour, which may be easily forecasted in a qualitative way.

Detailed micrographic analysis near the crack zone illustrates crack nucleation and propagation mode in the HAZ of the weldments, where most of the plastic strain cumulates.

BIBLIOGRAPHY

/1/ A. DEL PUGLIA, E. MANFREDI, G. TOMASSETTI - "High Temperature Fatigue Experiments on Welded Stainless Steel Tubular Elements" - Paper L 8/3, 4th SMiRT Conference, San Francisco 1977.

/2/ C. CARMIGNANI, E. MANFREDI, E. VITALE - "Influence of Weldments in the High Temperature Low Cycle Fatigue Resistance of AISI 304 and 316 Stainless Steel Tubular Elements" - Paper L 9/4, 5th SMiRT Conference, Berlin 1979.

/3/ C.R. BRINKMAN, G.E. KORTH, J.M. BEESTON - "Comparison on the Strain Controlled Low Cycle Fatigue Behaviour of SS 304/308 Weld and Base Material" - Int. Conf. on Creep & Fat. in El. Temp. Appl., Sheffield 1974.

/4/ P. PETREQUIN et al. - "Prise en compte de la fatigue oligocyclique dans la construction des réacteurs rapides refroidis au sodium" - Journée sur la Fatigue Oligocyclique ENSTA, Compiegne 1976.

/5/ Y.HIGASHIDA, J.D. BURK, F.V. LAWRENCE - "Strain Controlled Fatigue Behaviour of ASTM A36 and A514 Grade F Steels and 5083-O Alluminium Weld Materials" - Welding Journal, Nov.'78.

/6/ P.S. MAIYA, D.E. BUSCH - "Effect of Surface Roughness on Low Cycle Fatigue Behaviour of Type 304 S.S."- Metallurgical Transaction, Vol. 6A, 1975.

MATERIAL: AISI 304

CHEMICAL COMPOSITION (%)

C	Mn	Si	P	S	Ni	Cr
0.02	1.74	0.42	0.016	0.02	10.99	18.71

MECHANICAL PROPERTIES

T	°C	20	427	538	649
σ_y	MPa	277	167	150	133
σ_u	MPa	561	414	368	273
A	%	57.5			

MAIN TEST CONDITIONS

Temperature	T	650°	°C
Atmosphere	–	Air	–
Total Strain Range	$\Delta\varepsilon$	$0.45\div0.5$	%
Tensile Strain Rate	$\dot{\varepsilon}_t$	$3\div6\cdot10^{-4}$	s^{-1}
Compressive Strain Rate	$\dot{\varepsilon}_c$	$4\div6\cdot10^{-4}$	s^{-1}
Tensile Hold Time	h_t	$3\div4$	s
Compressive Hold Time	h_c	$3\div4$	s

Tab. I - Material and test parameters

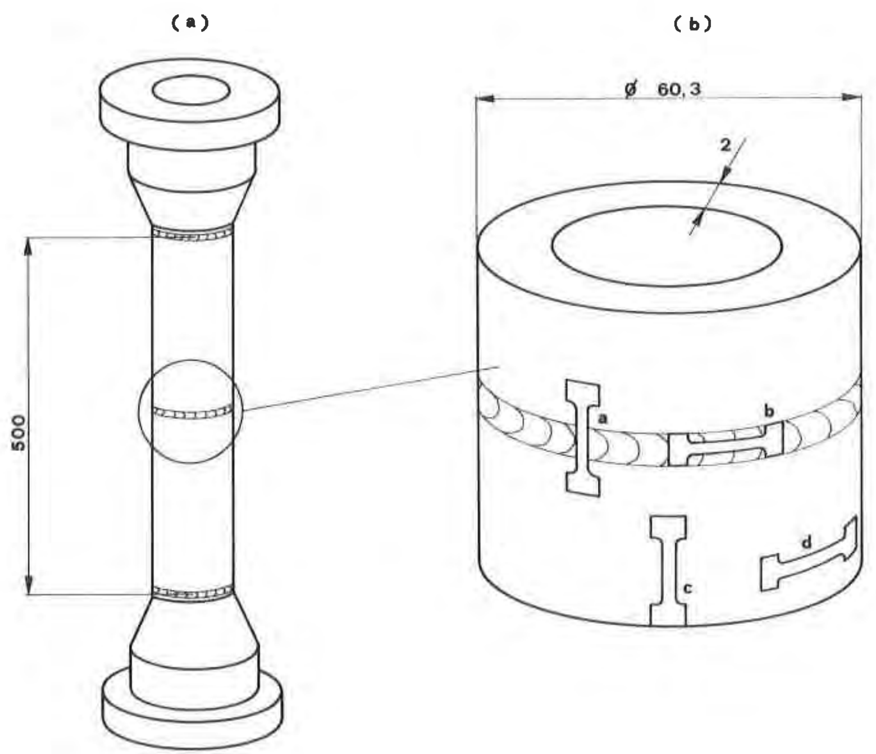

Fig. 1 - a) Specimen subjected to high temperature low cycle fatigue experiments

b) Samples drawn form different zones of the specimen.

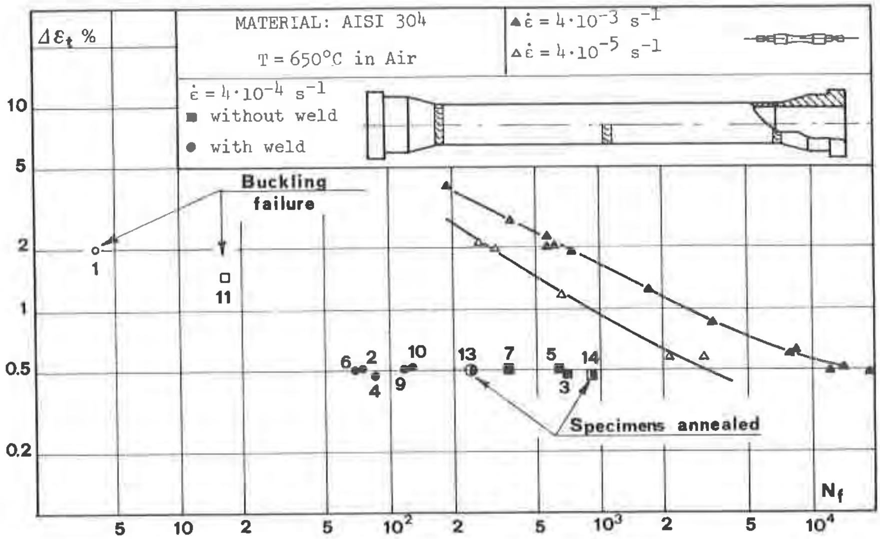

Fig. 2 - Review of experimental data obtained during the experiments, compared with smooth small size specimens data.

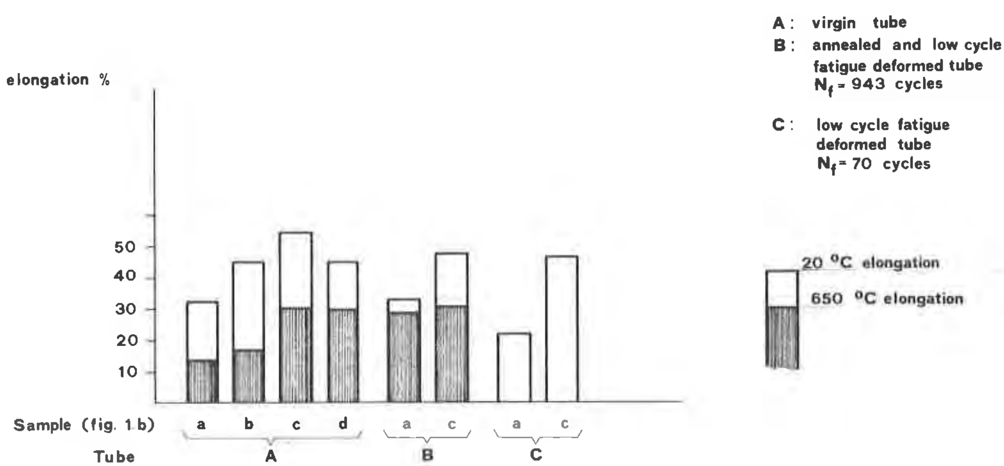

Fig. 3 - Monotonic ductility measurements performed at two temperatures with samples drawn as indicated in Fig. 1-b).

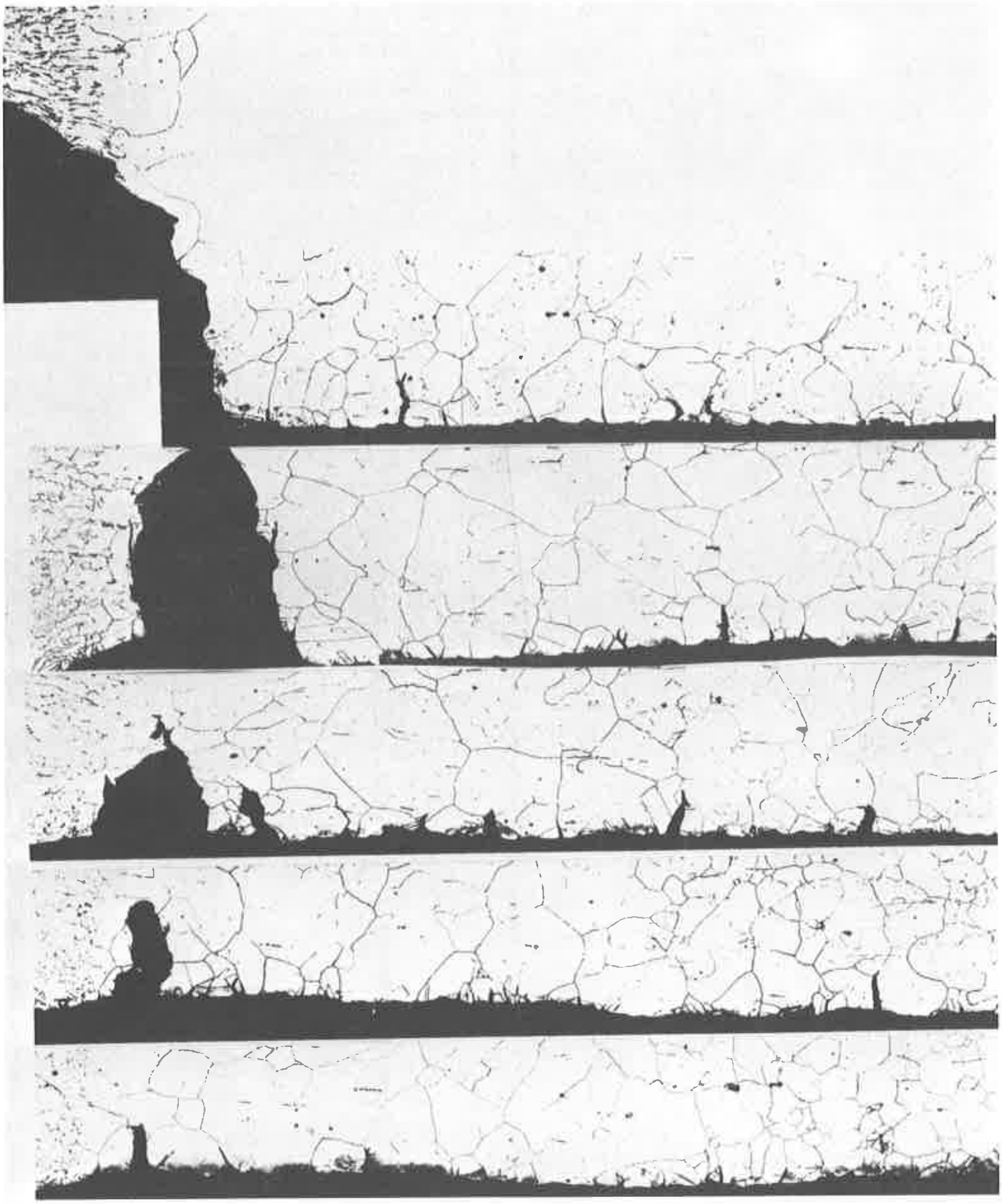

Fig. 4 - Failure zone micrography of a specimens fatigued at high temperature.