HIGH TEMPERATURE FATIGUE EXPERIMENTS ON WELDED STAINLESS STEEL TUBULAR ELEMENTS

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SUMMARY

One of the most important problems concerning the design of advanced type reactors regards the high temperature low-cycle fatigue behaviour of structural elements.

Design Guides and Codes report reference data, mainly based on strain range versus failure cycles results, which have been determined by various researchers. These data have been obtained through different test techniques applied to different type of specimens; common features are the small size of the specimens, the use of localized strain and the lack of any source of material non-homogeneity. As a consequence such data are not easily correlated; moreover at present an exhaustive series of results about high temperature low-cycle fatigue behaviour of structures is not available.

Therefore it seems interesting to investigate the reliability of existing basic data on the life prediction of simple structural elements, subjected to given high temperature load conditions, with the aim at determining the influence of such parameters as element size and geometry, material homogeneity, manufacturing effects (i.e. welding).

A test rig has been designed to perform high temperature fatigue experiments on AISI 304 stainless steel tubular elements of 500 mm length, 60.3 mm outer diameter and 2 mm thickness; they are composed by two butt welded tubular elements with welded end flanges.

During the experiments it is possible to control the axial strain range, the strain rate and the hold time; the specimen temperature is obtained by an inner heating device, controlled by a series of measuring thermocouples; until now the imposed temperature is 650 °C.

A preliminary series of experiments has been carried out, with the aim at getting informations for a proper development of the main experimental program, while in the meantime the adjustment of the specimen manufacturing process and its characterization have been performed. Each specimen is welded on the same TIG welding rig, which accounts both for a uniformly reliable welding process and for a proper alignment of the tubular elements. The specimens are then marked by a high precision grid which allows a measurement of the residual localized plastic strain along some generatrix of the specimen and on its thickness. The basic fatigue data have to be measured through a series of standard tests carried out on small size specimens obtained either from the base material and around the welded, heat affected zone. It is also planned to carry out a detailed study on the crack surfaces and to use acoustical emission techniques to properly assess the initial crack propagation.

The first results show a marked reduction of the number of cycles at failure, if compared with existing data about small size specimens; the measurement of residual plastic strains shows clearly non-uniform distribution of the plastic zones.

1. Introduction

This research at first has been partially supported by CNR (Consiglio Nazionale delle Ricerche), is now sponsored by CNEN (Comitato Nazionale per l'Energia Nucleare). The research is carried out by the University of Pisa, both organizations cooperating closely.

It is aimed at getting experimental informations about the behaviour of stuctural elements, when subjected to high temperature low cycle fatigue, roughly similiar to the conditions which are typical of high temperature nuclear reactor components. The results of such investigation are to be used for a better understanding of the significance and applicability of existing theories and data, which are at the root of available codes and Regulatory Guides [1, 2, 3].

For this reason it as been chosen, for a first experimental approach to the problem, a simple structural element composed by an AISI stainless steel tube segment with flanged ends, to be subjected to axial load cycling at temperatures ranging about 650°C.

This specimen incorporates several features, which are common to more complex structural elements: it has a larger size than most of the speciments, which have been mainly tested by other researchers; moreover it has been realized by means of materials and manufacturing techniques, which are close similiar to those used to manufacture larger structures, and which are apt to induce local alteration of metallurgical and mechanical properties, mainly owing to the welding process.

During the first phase of this research, it is planned to carry out several tests with costant load paramenters, about which the present paper is reporting. By this way it has made an effort to qualify properly the test procedures to point out new instrumentation and characterization techniques; moreover it has begun to deal with the complex problems of the HTLCF and to program the future experimental work, which will be, if possible, more methodically carried out.

In the following parts of this paper it will be illustrated the geometry and characterization procedure of the specimens, the test apparatus and some preliminary experimental results.

2. Geometry and characterization of the specimens

The size and geometry of the specimens (see fig. 1) have been chosen on the following basis:

- performances of the test apparatus;
- suitability to an easy measurement of the deformations.

These reasons have brought to design a specimen composed by a tube segment 500mm long with 60.3mm (2 in.) outer diameter, welded to two flanged ends.

Owing to the main philosophy of the research it has been decided to realize two types of specimens: the one with a single tube segment, the other whith a central circumferential butt weld joining two tube segments, each 250mm long.

Having planned to begin the experiments with AISI 304L tubes, owing to the test apparatus performances and to wall instability problems, it has chosen a thickness value about 2mm, although it does not correspond to a tube gauge for thermal appliances.

The material of the tubes has been utilized as purchased from the supplier and it has not been subjected to any peculiar Quality Assurance requirement.

On the other side the specimens have been manufactured following a characterization procedure, aimed at getting an experimental behaviour which is likely to repeat itself fairly.

The tube material, as supplied by Dalmine S.p.A., is strongly strain hardened and has a fine grain structure with some amount of impurities.

Chemical analysis and mechanical properties data, as given by the supplier, following the ASTM A 312 specification, are summarized by Table I. Further analysis and testing performed by CSN Casaccia Laboratories have shown a Carbonium content ranging about 300ppm, with marked differences between each other tube; Molybdenum content was about 0.3%. Ultimate strenght as high as 70 Kg mm^{-2} axially and about 60 Kg mm^{-2} circumferentially have been measured. These tests, however, have been performed on non standard specimens.

All the welds have been performed by means of a TIG pulsed arc automatic apparatus; central weld parameters being: $I_{max} = 100A$, $I_{min} = 40A$, heat input $\cong$ 1 KJoule mm^{-1}.

Macro and microhardness tests with load greater or equal to 100gr have shown quite constant values in the base material and in the HAZ. Microhardness tests with 50gr load are quite uncorrelated, HV values ranging from 143 to 192.

Ultimate tensile strenght of the central weld measured on non standard specimens was about 55 Kg mm^{-2}.

The flanged ends have been machined from thick AISI 304 tubes; the coarse grain structure of these parts has made it necessary to increase the minimum thickness up to 2.6 mm, as to avoid failures in this zone.

On the tubes it has been marked an accurate grid, by means of 4 axial lines and 20 transversal ones. This grid makes it possible to perform accurate local deformation and thickness measurements, either before and after each test.

To detect acoustical emission from some of the tested specimens it has been used a 16 mm diameter, 200 mm long steel rod brazed to a flanged end.

3. Test apparatus and procedure

The design of the test apparatus (see fig. 2) has been based on a specification calling for the following test conditions:

- to obtain, in the tube segment of the specimen, a controlled and uniform temperature, up to 650°C and over; the heat was to be generated by an irradiating source, being considered unsuitable to make use of the Joule effect;
- to apply a controlled amount of axial strain to the specimen, the maximum axial load being about 20,000 Kg either in extension and in compression;
- the total strain was to be prearranged before each test in a range mainly comprised between 0.5% and 2%; tensile and compressive strains were to be the same in each cycle;
- to control the strain velocity, which was to be varied between $4 \cdot 10^{-5} s^{-1}$ and $4 \cdot 10^{-3} s^{-1}$, as well as the hold time, that was to be comprised between 0 and 30 min.

The results of the tests have been detected and recorded by means of an instrumentation piloted by force and displacement transducers; by this way during each test have been traced hysteresis loops as well as stress or strain versus time records.

In the last tests it has become possible to get acoustical emission measurements with a "FRIDET" apparatus.

During each test it has measured on line the following parameters: applied load, total deformation, temperatures along the specimen, number of cycles, acoustical emission; it is planned to develop a system for the measurement on line of diametral and, possibly, axial local deformations.

On the specimen, while unmounted, by means of the grid marked on it are measured, out of line, residual plastic deformations.

Each test has been stopped when it has become apparent a marked reduction of the applied load.

4. Experimental results

Until now it has been carried out several tests either with specimens welded at mid point and without central weld. It is hoped that further results will be available in the next future, and about these latter it will be reported during the Conference.

The main informations are summarized by Table II. It has to be observed that all the centrally welded specimens have cracked along the central weld after fewer cycles than in the case of the specimens without central weld.

In fig. 3 is shown the variation of the load range ΔF versus the number of cycles, as observed in test No.6. The same illustration shows also acoustical emission data from the same test: it is shown the value of N (number of oscillations registered) and E (energy) per cycle versus the number of cycles. ΔF values are rather different from each other test, this fact being quite correlated with the variability of the mechanical properties of the material, as observed during the characterization procedure.

In the fig. 4 it is shown the number of cycles at failure versus imposed total strain; the same figure reports available data from experiments at the same temperature, by means of small size, "hour glass" shaped, machined and annealed specimens subjected to similiar load cycling under a strain control system piloted by diametral variation measurements [4, 5, 6, 7].

Cracks for each test are shown in figg. 5 ÷ 10, while fig. 11 shows a typical residual plastic deformation pattern, as measured after test No.4, near the crack.

5. Discussion of the results

The tests carried out until now have shown a marked reduction of the high temperature fatigue life of all the specimens, when compared with existing data obtained from small size specimens.

In the case of the specimens with central weld, which have had very early failures, it has to be observed that, owing to the tube menufacturing process, the hardness and mechanical properties of the cold drawn base material are considerably different from the ones of the weld itself, as it is previously indicated in this paper. It is probable that, trough the contrasting mechanisms of strain hardening and softening, the instant local plastic strain may largely exceed, in the weld zone, the average imposed strain. Continuous or spot check axial and diametral measurements, which are planned, will give a better insight into this aspect of the plastic behaviour.

The measurements of residual plastic strains show that in the zone near the crack there is a plastic strain pattern that markedly differs from the average imposed axial strain (see fig. 11). It is probable that only through a measurement on line of these deformations it will be possible to get a proper understanding of this phenomena.

The acoustical emission data, as illustrated by fig. 3, seem to show three different zones of emission: the first without almost any emission, the second with steadily increasing emission and the third with mean emission level rougly constant; from these scarce data cannot be derived any valid conclusion, but it is hoped that a coordinated use of the various experimental techniques will allow a better insight of the failure mode.

References

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[3] Design Guide for LMFBR Sodium Piping. (SAN - 781 - 1), Braun (C.F.) and Co., Alhambra, Calif.,1971.

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TABLE I

AISI 304 L						
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	kg mm^{-2}	28.3	17.0	15.3	13.6
σ_u	kg mm^{-2}	57.2	42.2	37.6	27.9
A	%	57.5	—	—	—

TABLE II

TEST	TYPE OF SPECIMEN	TEMPERATURE	HOLD TIME		STRAIN RATE	TOTAL STRAIN RANGE	CYCLES TO FAILURE	CRACK LOCALIZATION
No.	central weld	T °C	t_H ext	comp	$\dot{\varepsilon}$ s^{-1}	ε %	N_f	
1	yes	660	10	0	$4 \cdot 10^{-4}$	2	4	central weld buckling
2	yes	639	3	3	$4 \cdot 10^{-4}$	0.5	76	central weld
3	no	647	3	1	$4 \cdot 10^{-4}$	0.48	689	flanged end weld
4	yes	655	3	3	$4 \cdot 10^{-4}$	0.48	84	central weld
5	no	658	3	3	$4 \cdot 10^{-4}$	0.5	680	tube segment
6	yes	658	3	3	$4 \cdot 10^{-4}$	0.5	70	central weld

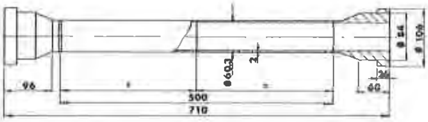

Fig. 1 - Specimen geometry

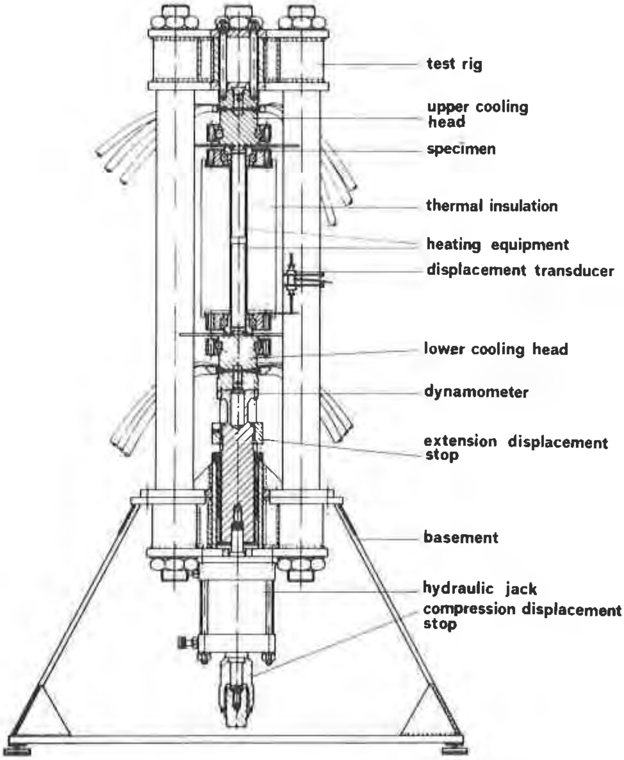

Fig. 2 - Test rig

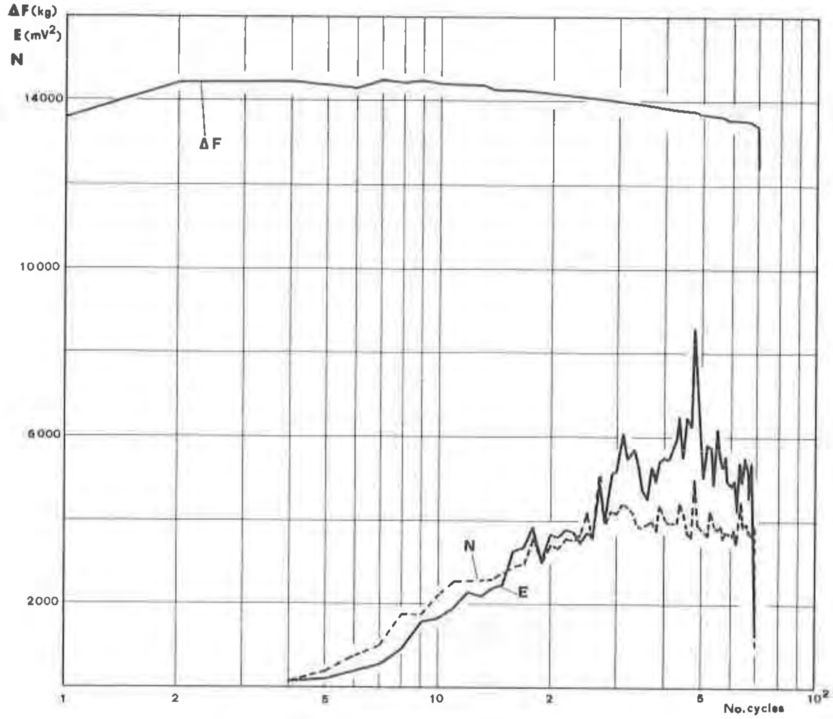

Fig. 3 - Load range and acoustical emission variation during test No. 6

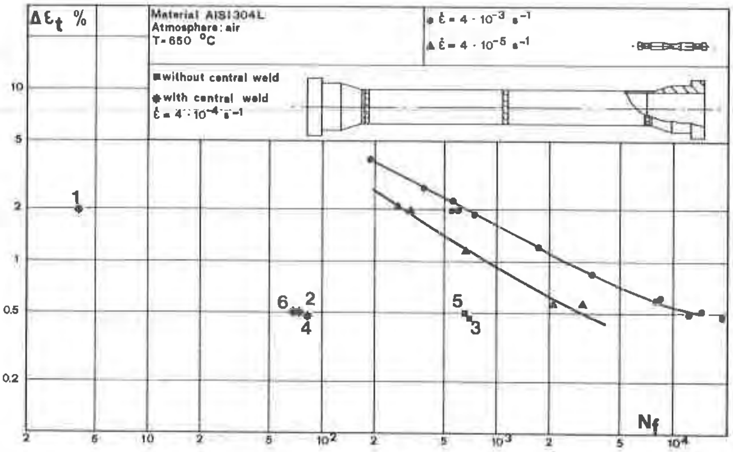

Fig. 4 - Fatigue life results compared with some existing data

Fig. 5 - Crack in test No. 1

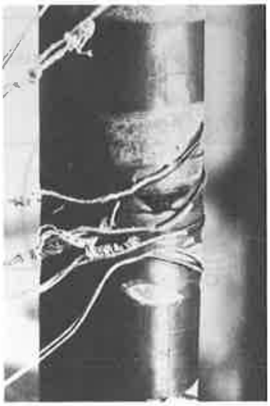

Fig. 6 - Crack in test No. 2

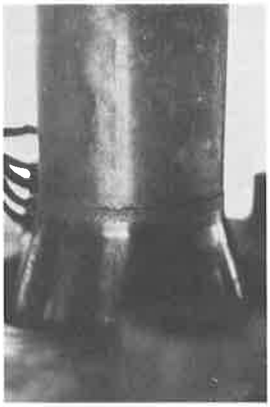

Fig. 7 - Crack in test No. 3

Fig. 8 - Crack in test No. 4

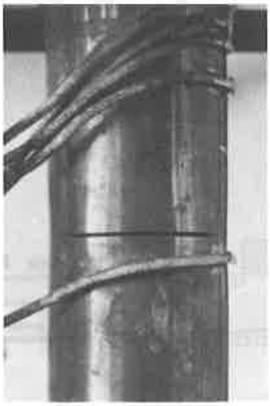

Fig. 9 - Crack in test No. 5

Fig. 10 - Crack in test No. 6

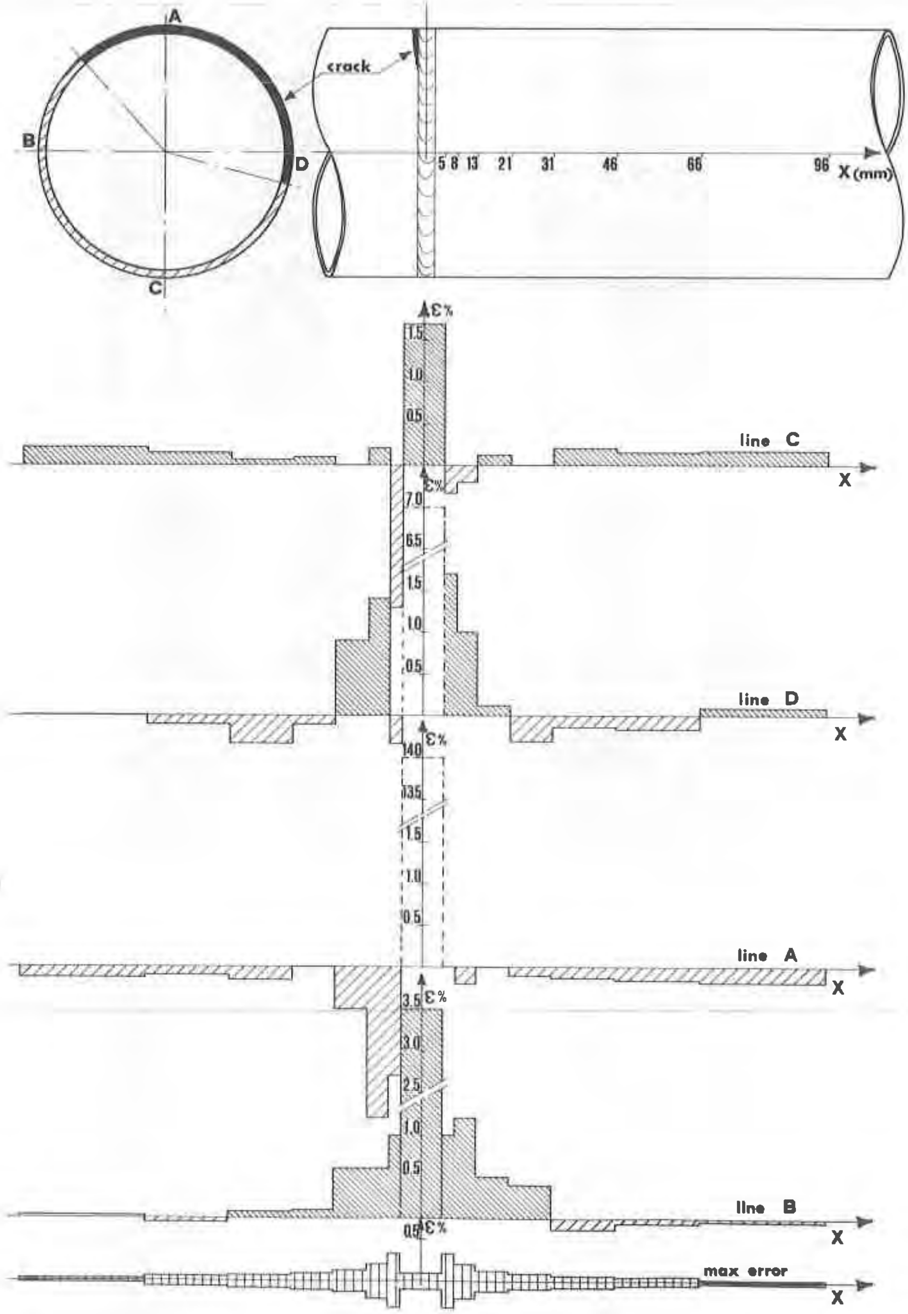

Fig. 11 - Residual plastic deformation after test No. 4