Experimental Determination of Material's Constitutive Laws and of Design Criteria of Reactor Structures in Extreme Dynamic Loading Conditions

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SUMMARY

A sound foundation of stress and/or strain criteria for the mechanical design of fast breeder reactor structures able to bear extreme dynamic loading conditions, passes through the experimental determination of dynamic mechanical properties of materials in end of life conditions with respect to the damaging processes to which the structures are submitted.

The calculation and verification of reactor structures following such design criteria requires that codes must be implemented by constitutive equations describing the dynamic mechanical response of the materials.

Dynamic mechanical properties of some austenitic stainless steels, such as AISI 321, AISI 316 L, AISI 316H, AISI 304L, DIN 4981, in virgin, welded, thermally aged and irradiated conditions, have been determined at strain rates up to 600 s^{-1}, temperatures up to 950°C. The dynamic response of virgin austenitic stainless steels at temperatures of 400°C and 550°C is not univocal passing from a substantial dynamic hardening behaviour to a dynamic softening behaviour, probably due to residual microstructural differences caused by the transformation processes. More homogeneous is the dynamic response of the same austenitic stainless steels damaged by welding, thermal ageing and irradiation. In fact, all these damaged materials, tested at 400°C and 550°C, show a dynamic softening behaviour and reduction of ductility.

When stainless steels, such as AISI 316 and AISI 304 are used to construct structures subjected to impulsive loadings, the designer must take into account that:

- at room temperature, the static tensile test values will give a conservative estimation of the dynamic strength of the material;
- at 400° and 550°C, the static tensile values are not conservative and reduction of ductility must also be taken into account. Hence safety margins and maximum allowable strain for extreme dynamic loading conditions must be checked by a programme of dynamic tensile tests of representative specimens (real size), previously submitted to the damaging processes acting on the real structure.

From the results obtained on small specimens, at the temperatures of 400°C and 550°C it follows that constitutive laws, for both virgin and damaged materials, which should have a minimum of prediction capability, must be founded on basic physical aspects such as dislocation dynamics, microstructural characteristics, concentration of defects.

1. INTRODUCTION

Fast breeder reactor structures which work at temperatures ranging from 400°C to 550°C, may be subjected to explosive accidents and impact of missiles giving rise to stress waves which deform the structures at high strain rate in the plastic domain. Due to the fact that inelastic structural analysis and life predictions are not completely developed, the plant safety protection against catastrophic failure must be achieved by applying conservative stress and/or strain criteria on the mechanical design of structures which must be able to bear extreme dynamic loading conditions. The sound foundation of these stress and/or strain limiting design criteria passes through the experimental determination of dynamic mechanical properties of materials in end-of-life conditions with respect to the damaging processes to which the structures are submitted, under loading conditions representative for the accidental one.

Therefore, the dynamic mechanical properties must be determined on materials degraded by the defects induced by the construction processes and by the real operative conditions of the reactor structures, which can be summarized as follows: welding, irradiation, thermal ageing in sodium, creep, thermal and mechanical fatigue, interactions between these various damaging effects.

Furthermore, the dynamic mechanical properties must be determined taking into account the effects of the complex loading situations created by an accident, which gives rise to: multiaxial stress state (mostly bi-axial), strain rate history (where generally $\dot{\varepsilon}$ is variable), strain history, Bauschinger effect due to unloading and reversed reloading.

Another important point which must be considered in determining the dynamic mechanical properties of structural materials is the size of the components, which could require the use of "real size" specimens, because strength and ductility are influenced by geometrical parameters and by distribution of defects that we have in the real structure. Weld joints especially require "real size" specimens because the three-dimensional state of stress due to temperature gradient in welding depends on the size of the welded piece.

The "real size" specimens permit also to investigate the influence on strength of macrodefects, such as cracks, which could appear during the life of reactor structures mainly near nozzles or in the heat affected zones.

A testing programme taking into account all these effects will permit to check the existing yielding criteria, hardening rules and failures theories and the development of constitutive equations able to describe the dynamic mechanical response of the materials.

More immediately the results obtained from this programme permit to establish empirical stress and/or strain limiting criteria for the mechanical design of components which should bear extreme dynamic loads.

The results of a screening programme of dynamic tensile tests performed on some austenitic stainless steels using small specimens (7 mm^2 cross section), are reported here. From the discussion of these results it will appear which elements must be checked using "real size" specimens and which must be considered in developing constitutive equations, stress and/or strain limiting design criteria.

2. MATERIALS AND EXPERIMENTAL PROCEDURES

The materials tested are the following:

- AISI 321 in virgin conditions;
- AISI 316L virgin, welded, welded + heat affected zone, thermally aged, irradiated to a fluence of 0.7×10^{22} n/cm^2, (E > 0.1 MeV);
- AISI 304L virgin, welded, welded + heat affected zone, thermally aged, irradiated to the same fluence;
- AISI 316H virgin, welded, welded + heat affected zone;
- DIN 4981 virgin.

Chemical composition of the steels are given in Table 1.

The dynamic uniaxial tensile tests have been performed at temperatures ranging from ambient temperature to 950°C placing the main efforts at the temperatures of 400°C and 550°C which are the working temperatures of fast breeder reactor structures. The specimens were heated by a small furnace in the case of virgin, welded and thermally aged materials, and by a direct current flowing through the specimen itself in the case of irradiated materials. The temperature was measured by a thermocouple placed on the specimen. The temperature variation along the active length of the specimen was $\pm$ 5°C. The equipment used to perform the tests consisted of the following items:

- a Hounsfield tensometer for strain rates of 10^{-2} s^{-1};
- a hydropneumatic machine /1/ for strain rates ranging between 1 s^{-1} and 100 s^{-1};
- a modified Hopkinson bar /1/ for strain rates ranging between 100 s^{-1} and 1000 s^{-1}.

A short specimen was used having an active length of 5 mm and 3 mm diameter as required by the Hopkinson's bar principle, which achieves the homogeneous stress distribution in the specimen by successive reflections of the elastoplastic waves travelling through the specimen itself.

3. RESULTS REGARDING VIRGIN MATERIALS

At room temperature the flow curves of all the materials mentioned before show dynamic hardening behaviour where flow stress at a given strain increases and both uniform elongation and fracture elongation decrease with increasing strain rate, as can be seen on Figs. 8, 9, 10 for AISI 316L virgin. At high temperature the material response is more complicated depending on the different materials and on the temperature magnitude:

- at 400°C the flow curves of AISI 316L /2/, AISI 321, show a moderate dynamic

hardening behaviour where flow stress at a given strain increases and uniform and fracture elongation slightly decrease with increasing strain rate. The flow curves of AISI 316H /3/ (Fig. 1) show a more accentuated dynamic hardening behaviour and reduction of ductility with increasing strain rate. Always at 400°C the steel AISI 304L /4/ showed substantially no influence of strain rate on the flow curves except a slight increase of 0.2% yield stress and a slight decrease of uniform deformation with increasing strain rate;

- at 490°C the steel DIN 4981 /1/ (Fig. 2) showed a moderate dynamic softening behaviour where the flow stress at a given strain slightly decreases with increasing strain rate and ductility remains nearly constant;
- at 550°C the flow curves of the steel AISI 316L (Fig. 3) and AISI 304L were substantially insensitive to strain rate except a slight increase of 0.2% yield stress and a slight decrease of uniform deformation with increasing strain rate;
- at the high temperatures of 750°C and 950°C /2/ the flow curves of AISI 316L and AISI 321 show a strong dynamic hardening behaviour where flow stress at a given strain increases up to three times the static value and fracture strain remains nearly constant with strain rates up to 10 s^{-1} and decreases (AISI 321) or increases (AISI 316L) for strain rates up to 450 s^{-1}.

4. RESULTS REGARDING MATERIALS DAMAGED BY WELDING, THERMAL AGEING, IRRADIATION

The materials welded using electric argon technique were AISI 316L /3/ and AISI 316H /3/. Specimens were constructed from the weld material, from the heat affected zone material, from both the weld and the heat affected zone material. At high temperature (400°C and 550°C) all these materials damaged by welding show a dynamic softening behaviour where the dynamic flow curves mainly lie below the static curve and ductility decreases with increasing strain rate. An example of this behaviour is shown in Fig. 4 regarding AISI 316H weld and heat affected zone where the behaviour of the corresponding virgin material is shown in Fig. 1. The main dynamic mechanical properties of 316H virgin, weld, weld + H.A.Z. are reported in Figs. 6 and 7. Specimens of AISI 304L /4/ and AISI 316L /5/ were thermally aged at 400°C, in a sodium environment, for a time of 3264 hrs. These thermally aged materials, tested at 400°C and 550°C, showed also a dynamic softening behaviour characterized by a decrease of flow stress and uniform elongation with increasing strain rate. These phenomena are more accentuated at 550°C. Dynamic softening and reduction of uniform deformation were also shown by AISI 304L /4/ and AISI 316L /5/ irradiated up to 2.2 dpa, tested at 400°C and 550°C as shown in Figs. 5, 8, 9, 10, regarding AISI 316L, with an accentuation of these phenomena at 550°C. At room temperature all the welded, thermally aged and irradiated materials here mentioned showed a dynamic hardening behaviour with an increase of flow stress and reduction of ductility with increasing strain rate as mentioned in the foregoing chapter for the corresponding virgin steels and as shown in Figs. 8, 9 and 10 regarding AISI 316L.

5. DISCUSSION OF THE RESULTS

The results reported on some virgin austenitic stainless steels tested at the working temperatures (400°C + 550°C) of fast breeder reactor structures, show that the effects of high strain rate on the mechanical properties vary strongly passing from one material to the other. In fact, from a marked dynamic hardening behaviour and reduction of ductility (AISI 316H at 400°C), one passes to moderate dynamic hardening and reduction of ductility (AISI 316L at 400°C), to practically no strain rate sensitivity (AISI 304L at 400°C and 550°C, AISI 316L at 550°C), to dynamic softening (DIN 4981 at 490°C). At the same test temperatures (∿400°C and ∿550°C) Steichen /6, 7/ reports a very moderate dynamic hardening and no changes of ductility of virgin AISI 304 and AISI 316, while Isozaki's results /8, 9/ show a noticeable dynamic softening and no practical changes of ductility for the virgin SUS 304 and SUS 316 stainless steels. Considering the results reported here at temperatures of 400°C and 550°C, on austenitic stainless steels damaged by welding, thermal ageing, irradiation, one observes a pronounced dynamic softening and reduction of ductility. Dynamic softening and no practical changes of ductility are reported by Isozaki /8, 9/ for the welded SUS 304 and SUS 316, tested at 400°C and 550°C. Steichen /10/ tested at 525°C AISI 304 irradiated to a fluence of 0.75×10^{22} n/cm^2 (E > 0.1 MeV), at strain rates up to 100 s^{-1}, test and irradiation conditions being very near to those realized by us on our AISI 304L; flow stress was practically insensitive to strain rate while fracture and uniform elongation substantially increase with strain rate. As referred to by Steichen /7/ and Campbell /11/, this softening behaviour is probably due to interactions between diffused interstitial carbon and nitrogen atoms with dislocations. This instability which probably starts immediately after the elastic deformation before striction begins (see Fig. 2), is accentuated by the increasing strain rate and seems to be also influenced by the grain size /12/. The dynamic response of virgin austenitic stainless steels at temperatures of 400°C and 550°C is not univocal passing from a substantial dynamic hardening behaviour to a dynamic softening behaviour, probably due to residual microstructural differences caused by the transformation processes. More homogeneous is the dynamic response of the same austenitic stainless steels damaged by welding, thermal ageing and irradiation. In fact, all these damaged materials, tested at 400°C and 550°C, show a dynamic softening behaviour and reduction of ductility which indicate that the microdefects induced by the different damaging processes govern in the same way the dynamic response of these damaged materials. Similar results have been found by us and by Steichen /7/ regarding the large increase in strength and ductility of the austenitic stainless steels AISI 304 and AISI 316 tested at temperatures from 750°C to 950°C with increasing strain rate. Similar results have been also found by us, Steichen, Isozaki, regarding a substantial dynamic hardening and a reduction of ductility of austenitic stainless steels AISI 304 and AISI 316 tested at room temperature.

6. INDICATIONS FOR THE DEVELOPMENT OF DESIGN CRITERIA FOR DYNAMICALLY LOADED STRUCTURES

The results obtained from the screening test programme on small specimens indicate

that, when stainless steels such as AISI 316 and AISI 304 are used to construct structures subjected to impulsive loadings, such as sudden increase of pressure in the vessel in case of an accident, the designer must take into account that:

- at room temperature, the static tensile test values will give a conservative estimation of the dynamic strength of the material;
- at 400°C and 550°C, the static tensile values are not conservative and reduction of ductility must also be taken into account, leading to the necessity of determining reducing factors on the maximum allowable stress and strain used for statically loaded structures.

Developing the lines of a test programme for determining the maximum allowable stress and strain for dynamically loaded structures, particular attention must be given to the weld joint operating at temperatures of 400°C and 550°C. In fact, we reported before that the dynamic response of virgin material is different from that of welded material. We remember as an example that virgin AISI 316H (Fig. 1) showed a marked dynamic hardening while welded AISI 316H showed dynamic softening (Figs. 4, 6, 7). This marked difference of the dynamic mechanical properties of virgin and welded material could cause three-dimensional stress field around the weld creating conditions favourable to brittle fracture, in any case concentrating the deformation in the weld joint while the weld material has often the lowest ductility in comparison with virgin and heat affected zone material. Therefore, the dynamic strength and the deformation capability of a weld joint must be evaluated on plate shaped specimens having size near the real one on which real weld joint can be realized in order:

- to include the effects of the residual stresses;
- to realize the stress and deformations concentrations created by the different mechanical properties of the virgin and weld material;
- to have a statistical distribution of defects representative for the real one, including defects created by thermal ageing, creep, fatigue;
- to reproduce the same geometrical conditions in which the plastic flow of the material takes place in a plate which is the most used structural shape;
- to investigate the effects on weld joint strength caused by loading longitudinal and transversal with respect to the joint axis. In fact, longitudinal loading imposes equal deformation to virgin, heat affected zone and welded material giving rise to cracks in that material with the lowest ductility. Transversal loading starts deformation in that material that has the lowest elastic limit, where fracture will occur;
- to investigate the effects of biaxial loading which includes the contemporaneous longitudinal and transversal loading.

The experimental procedure aimed to determine the reducing factors to be applied to the static strength and ductility data of the materials in begin-of-life conditions could be that of determining the reducing factors caused by each single damaging process and to combine their effects performing tests on specimens where two or more damaging processes interact. In order to investigate these problems, we are constructing a dynamic high load (5 MN) apparatus able to test plate specimens having cross section up to 5000 mm^2,

corresponding to that of a real size weld point.

7. INDICATIONS FOR THE DEVELOPMENT OF MATERIALS CONSTITUTIVE LAWS IN DYNAMICS

From the results here reported it appears how difficult will be the development of constitutive laws describing the dynamic response of austenitic stainless steels. In fact, the results obtained testing at high temperature (400°C and 550°C) virgin austenitic stainless steels show that the general trend of the dynamic flow curves passes from a marked dynamic hardening behaviour to a dynamic softening behaviour probably in dependency of small changes of the microstructure and their interactions with dislocation movements. At the same test temperature, more homogeneous is the dynamic response of materials damaged by welding, thermal ageing, irradiation, where the defects always govern the dynamic flow curves to unstable dynamic softening. It follows that constitutive laws for both virgin and damaged materials, which could have a minimum of prediction capability, must be founded on basic physical phenomena such as dislocation dynamics, microstructural characteristics, concentration of defects. An effort must be made in order to measure grain size, nature, size and frequency of defects, before, after, and eventually during testing, in order to define microstructure and defects parameters, damage laws which must enter the constitutive law. Experiments at high strain rate must be developed where the strain laws can be correlated with microstructural parameters and dislocations theory. An example of these experiments are those proposed by Shioiri /13/ who deduces dislocation density and velocity from ultrasonic attenuation and velocity measurements performed on specimens deformed at high strain rate using an Hopkinson bar. Measurements of strain distribution directly on the specimen in function of time by high sensitive interferometric methods should enable us to discriminate between the effects of dynamic softening and restriction of area instabilities.

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MATERIAL	FABRICATION PROCESS	CHEMICAL COMPOSITION % Wt									
		Cr	Ni	Mn	Mo	Nb	C	Si	S	P	Ti
AISI 316 L	HOT ROLLED PLATE SOLUTION TREATED	16.0	13.3	1.82	2.74	< 0.01	0.03	0.4	0.007	≤0.05	–
AISI 304 L	HOT ROLLED BAR ANNEALED	18.9	9.2	1.88	0.27	< 0.01	0.02	≤0.1	0.004	≤0.05	–
AISI 321	HOT ROLLED PLATE ANNEALED	16.7	10.25	1.84	–	–	0.07	0.25	0.01	0.032	0.38
DIN 4981	COLD WORKED SHEET	16.5	16.5	1.25	1.8	< 1	0.1	0.45	–	–	–
AISI 316 H	HOT ROLLED PLATE	17.47	11.64	1.31	2.63	–	0.04	0.31	0.020	0.023	–

TABLE 1 CHEMICAL COMPOSITION AND FABRICATION PROCESS

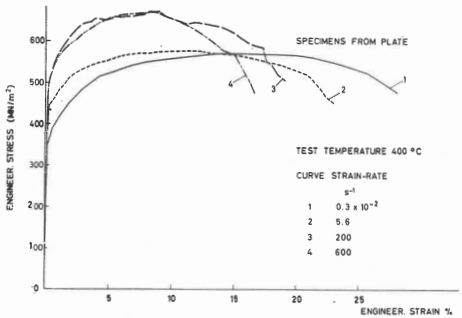

Fig.1 : STRESS-STRAIN CURVES FOR 316 H STAINLESS STEEL, VIRGIN.

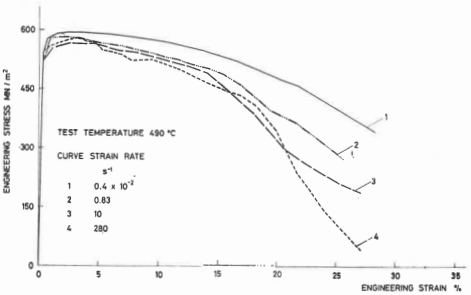

Fig. 2 : STRESS-STRAIN CURVES FOR DIN 4981 STAINLESS-STEEL , VIRGIN.

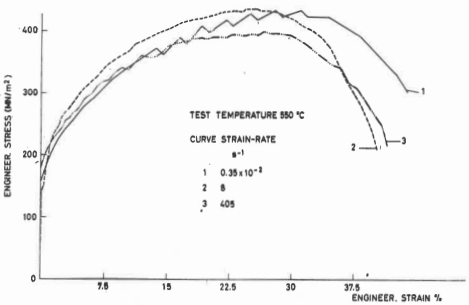

Fig. 3 : STRESS-STRAIN CURVES FOR AISI 316L STAINLESS STEEL, VIRGIN

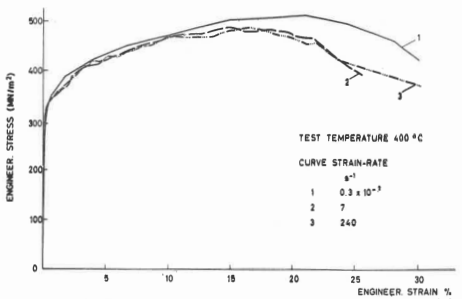

Fig.4 : STRESS-STRAIN CURVES FOR 316 H STAINLESS STEEL WELD+HEAT AFFEC_ TED ZONE

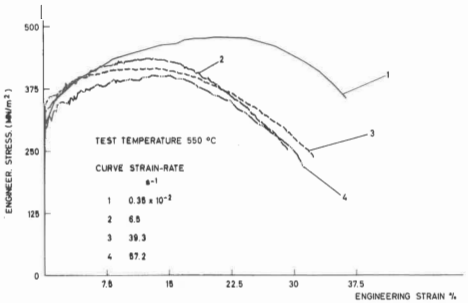

Fig. 5 : STRESS-STRAIN CURVES FOR AISI 316 L STAINLESS STEEL IRRADIATED TO 2.2 DPA.

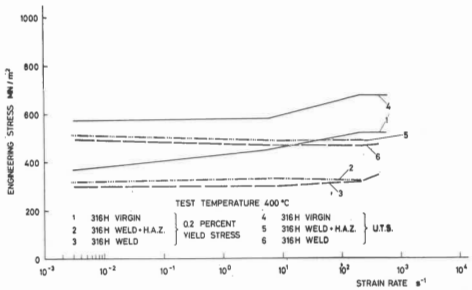

Fig.6 : EFFECT OF STRAIN-RATE ON THE 0.2 PERCENT YIELD STRESS AND ON ULTIMATE TENSILE STRESS OF 316 H STAINLESS STEEL , VIRGIN , WELD, WELD + HEAT AFFECTED ZONE.

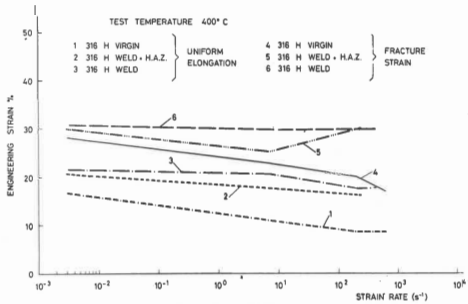

Fig. 7: EFFECT OF STRAIN RATE ON THE UNIFORM ELONGATION AND ON THE FRACTURE STRAIN OF 316 H STAINLESS STEEL, VIRGIN, WELD, WELD + HEAT AFFECTED ZONE.

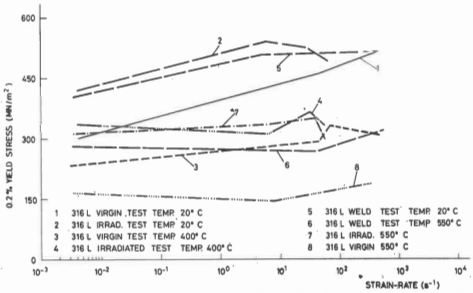

Fig. 8 : EFFECT OF STRAIN RATE ON THE 0.2 PERCENT YIELD STRESS OF 316 L S.S. VIRGIN, WELDED, IRRADIATED TO 2.2 DPA AT 400° C

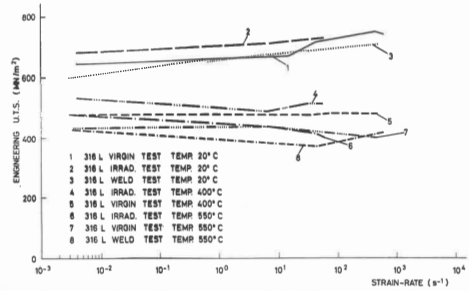

Fig. 9 : EFFECT OF STRAIN-RATE ON THE ENGINEERING ULTIMATE TENSILE STRESS OF AISI 316L STAINLESS STEEL VIRGIN, WELDED, IRRADIATED TO 2.2 DPA AT 400° C.

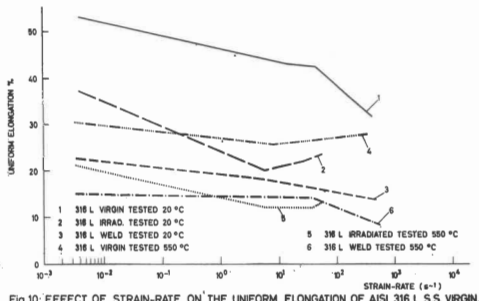

Fig.10: EFFECT OF STRAIN-RATE ON THE UNIFORM ELONGATION OF AISI 316 L S.S. VIRGIN, WELD, IRRADIATED TO 2,2 DPA AT 400 °C.