CONSTITUTIVE EQUATIONS FOR USE IN DESIGN ANALYSES OF LONG-LIFE ELEVATED TEMPERATURE COMPONENTS*

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EXTENDED ABSTRACT

This paper addresses design analysis needs and procedures relative to elevated temperature components in liquid metal fast breeder reactor (LMFBR) systems. Parts of LMFBR systems operate for significant portions of their 30 to 40 year design lifetimes at temperatures that are sufficiently high for time-dependent (creep) deformations to occur. Periodic shut-down events cause the components to experience thermal transients which combine with pressure loadings to produce complex inelastic behavior at temperatures within the creep regime of the structural alloys. The effects of the thermal transients on the pressure boundary components are enhanced by the excellent heat transfer properties of the liquid sodium coolant.

Design criteria for high-temperature nuclear reactor components recognize the potential occurrence of inelastic structural response. Specifically, criteria and limits, such as those in ASME Code Case N-47, have been developed that reflect a recognition of this potential and employ design-by-analysis concepts that can require that inelastic (elastic-plastic and creep) analyses be performed to satisfy the criteria and limits. However, the ASME documents have not included guidance on how inelastic analyses should be carried out, leaving it to the component owners to select the methods to be employed. Therefore, the Oak Ridge National Laboratory (ORNL) has undertaken on behalf of the Department of Energy, coordinated experimental and analytical efforts to establish appropriate constitutive equations for representing multiaxial time-dependent responses of LMFBR alloys. This presentation describes progress that has been made in recent years. Special attention is given to activities relevant to the development of equations applicable under cyclic loading conditions.

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The general process through which many of the present LMFBR structural analysis guidelines have been developed is discussed in Ref. 1. This process has led to a framework that is in place for three alloys, and aspects of the inelastic analysis capabilities have been discussed earlier in Refs. 2 and 3. Most of the developments discussed here are given in terms of constitutive equations that are based on theories of continuum mechanics that separate elastic, plastic, and creep strains. However, progress is being made in developing equations that are based on "unified measures" of inelastic strains and "state variables" that do not make such a distinction. This progress is also addressed in this symposium by Robinson. A discussion of overall progress in these areas is given in Ref. 2.

The basic analytical framework is first to be discussed, but a major focus is on improved representations of interactions between time-independent (elastic-plastic) and time-dependent (creep) responses of materials. The elastic-plastic model is based on a modified linear kinematic hardening model that permits the occurrence of limited isotropic hardening. The creep model is based on an equation-of-state approach that uses strain-hardening and stress as state variables. The strain-hardening measure has been defined relative to history-dependent reference stresses in order to be applicable to cyclic loadings. Both the elastic-plastic and creep models are formulated in general multiaxial terms.

Although, it has been recognized for a long time that plastic and creep deformations influence one another at elevated temperatures, it has been difficult to understand the nature of these influences to the degree where they can be incorporated into constitutive equations intended for design use. The difficulties include identifying the potentially important interactions, understanding their magnitude and longevity, representing them with mathematical models, and understanding the consequences of interaction models for loading conditions other than the ones from which they were initially developed. The concerns about interactions have been from two perspectives. In the first, observations are made on the representation of influences of cyclic plastic straining on subsequent creep beahvior. In the second, representations of elastic-plastic behavior are examined while considering influences of prior and interspersed creep straining or periods of stress relaxation. This presentation addresses the former more than the latter. Further observations concerning the latter can be found in Ref. 3 through 5.

Figures 1 and 2 show stress relaxation responses of a specimen of 2-1/4 Cr—1 Mo steel subjected to successive loadings to illustrate one type of interaction between creep and plastic deformations. In each sequence, the specimen is subjected to repeated stress relaxation intervals that start with approximately the same initial stress [103 MPa (15 ksi)] at 538°C (1000°F). In the first test sequence, the tensile load in the specimen is increased directly to the maximum value at the end of the constant strain (relaxation) hold period. In the second test, the specimen is loaded in the compressive direction to prescribed compressive plastic strain values and then loaded to the maximum tensile stress. (The loading histories are shown schematically in Figs. 3 and 4.) It is clearly seen that the reversed plastic loadings influence the subsequence resistance to creep deformation. The constitutive equations currently employed in LMFBR design evaluations recognize this type of interaction.

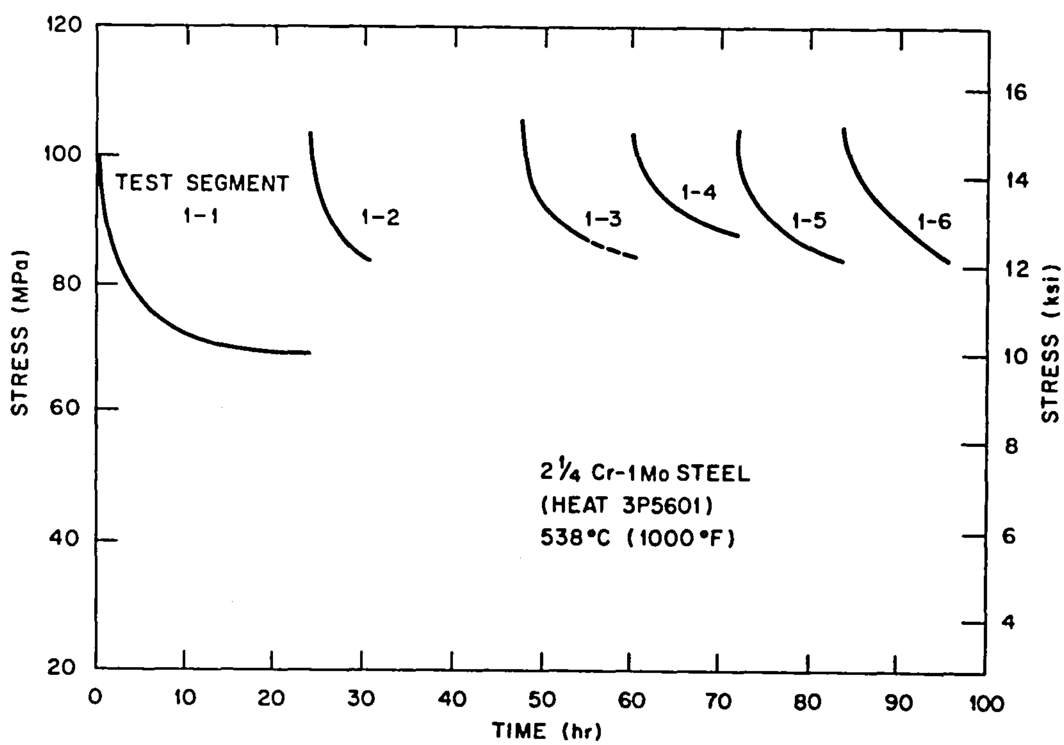

Fig. 1. Stress relaxation response of a 2-1/4 Cr—1 Mo steel specimen repeatedly loaded to an initial stress of 103 MPa (15 ksi) at 538°C (1000°F).

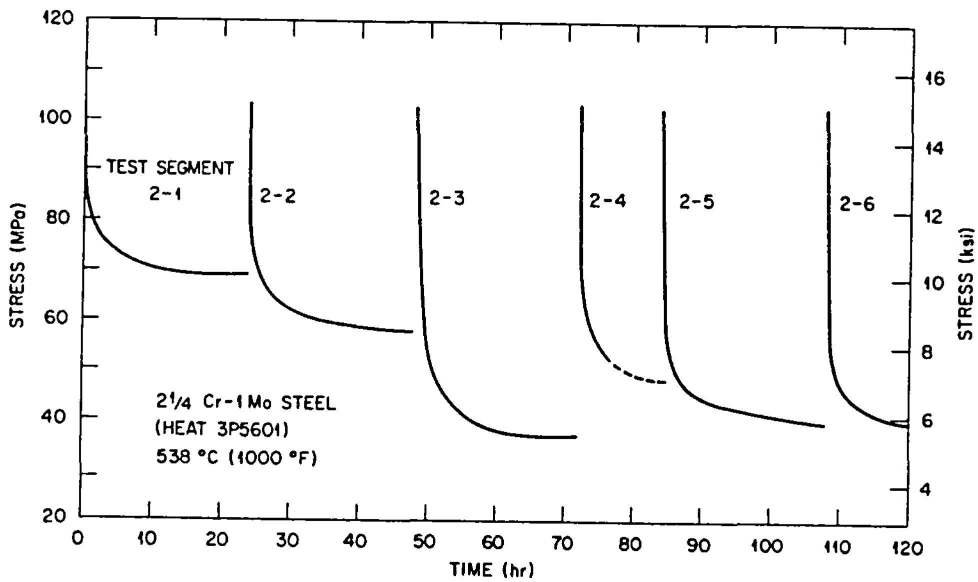

Fig. 2. Relaxation response of the 2-1/4 Cr—1 Mo steel specimen employed in Fig. 1 to successive loadings separated by reversed plastic cycles.

References

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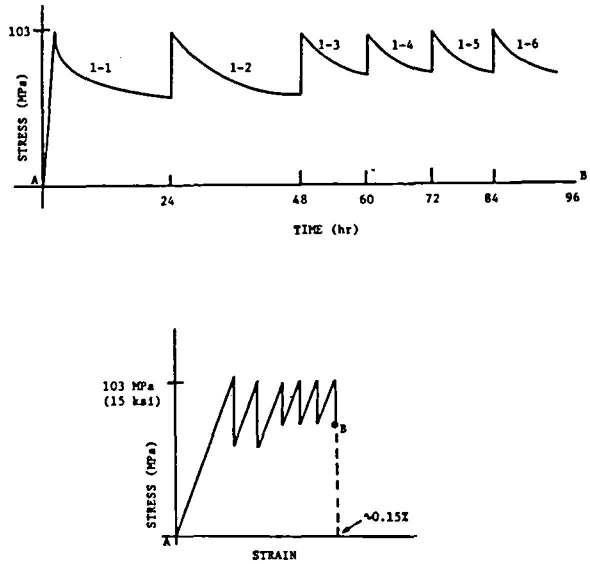

Fig. 3. Schematic of loading used in the cyclic relaxation test shown in Fig. 1 for 2-1/4 Cr–1 Mo steel specimen, 538°C (1000°F); six segments of relaxation following repeated monotonic loading to 103 MPa (15 ksi).

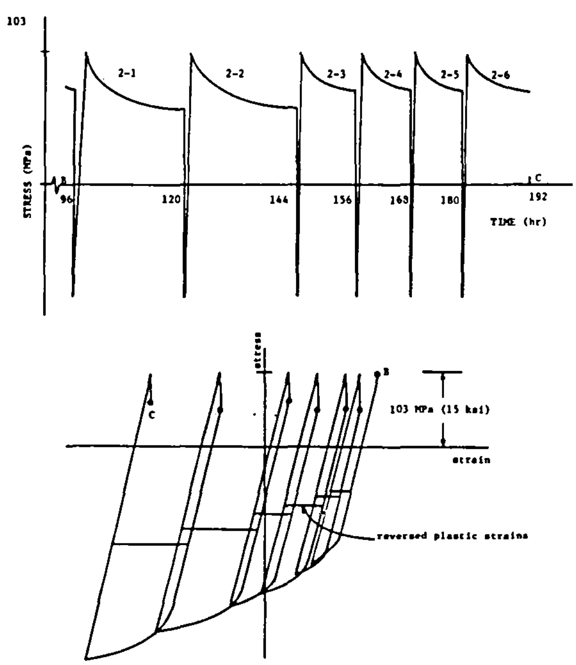

Fig. 4. Schematic of relaxation loading shown in Fig. 2 for 2-1/4 Cr–1 Mo steel specimen, 538°C (1000°F); six segments of relaxation following reversed plastic straining and reloading to 103 MPa (15 ksi).