HIGH TEMPERATURE DEFORMATION OF HASTELLOY ALLOY C-276

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ABSTRACT

High temperature deformation of Hastelloy alloy C-276 was studied. Hot compression tests were carried out at 1900, 2000, 2050 and 2100°F and at strain rates ranging from 10^{-3} to 1 sec^{-1}. The relationship between flow stress, strain, strain rate and temperature was examined and the mechanical equation of state was developed. Stress, strain and strain rate behavior at 2100°F was found to be markedly different from that at 1900 and 2000°F. The material showed a high degree of strain hardening at 2100°F. The activation energy for the deformation of Hastelloy alloy C-276 was found to be 109 Kcal/mole which is much higher than the activation energy for self-diffusion of nickel. It is suggested that dynamic recrystallization could be the rate-controlling mechanism. Microstructure examination revealed that recrystallization was promoted by higher temperature and higher deformation speed.

Introduction

Hastelloy* alloy C-276 is a wrought nicke-base superalloy with high strength and excellent corrosion resistance to a wide variety of chemical environments. The high strength and corrosion resistance of this alloy is attributed to the continous matrix of fcc Ni-base solid solution of Cr, Co, Mo, W, Fe etc. in high amount. Since most of the superalloys are designed to resist deformation at high temperature, it is not surprising that they are very difficult to deform. High concentration of dissolved alloying elements (40-50%) gives rise to higher flow stress and also higher recrystallization temperature, thus narrowing the temperature range for hot working.

The objective of the present study was to determine the high temperature deformation characteristics of Hastelloy alloy C-276. Ductility and strength are the main properties that determine the workability of a material. These properties are inherent physical property of a material and depend on variety of factors, e.g. chemical composition, metallurgical structure, speed of deformation and temperature etc. The purpose to this study was to determine the relationship between flow stress, strain, strain rate and temperature, namely the mechanical equation of state for Hastelloy alloy C-276. It was also aimed at studying the deformation mechanism and the operative softening and hardening processes of this alloy as well as the resulting microstructures.

Experimental Program

In this study axisymmetric compression testing is carried out to evaluate the hot deformation behavior of Hastelloy alloy C-276. Compression test was selected for its ease and for the simplicity of the specimen geometry. Moreover, the test does not suffer the strain limitation imposed by necking as is the case in tension; and therefore high strains as those achieved in forming processes can be obtained. In addition, in most of the large plastic deformation processes (rolling, forging, extrusion, etc.) the state of stress is largely that of a compressive type than a tensile state.

Material

Hot compression testing was carried out on Hastelloy alloy C-276 in the as-received mill-annealed condition. Compression specimens of 0.750 in. in diameter and 0.750 in. in height were provided by Stellite Division of Cabot Corporation. Microstructure is shown in Fig. 1 and the chemical composition of the alloy is given in Table I.

Table I

Hastelloy Alloy C-276 Chemical Composition (Wt %)

Ni	Co	Cr	Mo	W	Fe	Si	Mn	C	Others
Bal	1.74	15.16	15.51	3.98	5.45	< 0.01	0.46	0.002	V = .08 P = .024 S = .007

Equipment and Testing

Compression tests were performed on an electrohydraulic mechanical testing system (MTS) capable of providing loads up to 180,000 lbs. and speeds up to 0.5 in/sec. A quad-elliptical radiant heating furnace was used. The furnace was provided with a 0.5" diameter quartz observation window to permit specimen viewing during deformation and a 0.25" diameter hole for thermocouple attachment to control and measure specimen temperature. Compression die blocks made of

*"Hastelloy" is a registered trade mark of Cabot Corporation.

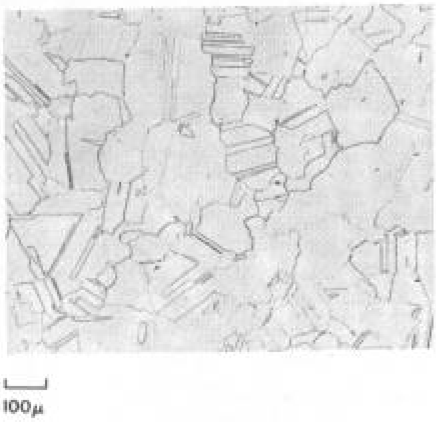

Figure 1. Microstructure of Hastelloy Alloy C-276 in as-recieved condition.

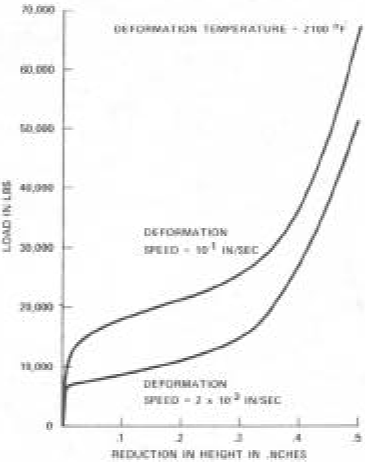

Figure 2. Load Deformation Curves During Compression.

Haynes* alloy 188, 2.25" in diameter were used. The end faces of die-blocks were ground flat and parallel.

The die-blocks and specimen were first cleaned and coated with borosilicate glass lubricant. The specimen was then placed and centered between the die-blocks and heated to desired test temperature. The specimen was held at test temperature for 10 min. before deformation. Compression test was carried out until a reduction in height of about 70% was achieved. A constant test temperature within ± 5°F was maintained throughout a test. Load displacements were continuously recorded during deformation. After deformation, the specimen was water quenched to retain the microstructure resulting from deformation.

Hot compression results were obtained at various cross-head speeds ranging from 10^{-3} to 10^{-1} in/sec and at temperature of 1900°, 2000°, 2050° and 2100°F.

Results and Discussion

Stress-Strain-Strain Rate

Typical load-displacement curves obtained by hot compression of Hastelloy alloy C-276 at 2100°F and for two different deformation speeds are shown in Fig. 2. Similar curves for other temperatures and speeds were obtained. The increase in load due to increase in deformation speed can be seen in Fig. 2. From the load-displacement curves, stress, strain and strain rate were calculated as follows:

$$\text{True Strain } \bar{\varepsilon} = \ell n\left(\frac{h_o}{h_i}\right)$$

$$\text{True Strain Rate } \dot{\bar{\varepsilon}} = \left(v/h_i\right) \quad \text{in/in/sec}$$

$$\text{Flow Stress } \bar{\sigma} = \left(L/A_i\right) \quad \text{psi}$$

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where h_0 is original height, h_i is instantaneous height, v is cross-head speed, A_i (= A_0h_0/A_i) is instantaneous area and A_0 is original area.

At given temperature and deformation speed, the flow stress, strain, and strain rate continuously vary throughout the test. Figs. 3(a,b,c,d) show the stress, strain and strain rate values at different temperatures. The effect of strain on the stress-strain rate relationship can be examined by comparing values corresponding to the lowest and highest strain shown by the two dotted lines. In the high strain-rate range the effect of strain on the flow stress is small while at low-strain rates the effect of strain on the flow stress is more pronounced. The flow stress shows a high degree of strain dependency in the temperature range of 2050 to 2100°F and for the full range of the strain rate considered in these tests (Figs. 3c and 3d).

Mechanical Equation of State

In the analysis of different metal forming processes, it is useful to have an empirical relationship between the flow stress, strain, strain rate, and temperature of the material. Several empirical equations that closely fit the experimental observation have been used for a variety of metals and alloys (Ref. 1, 2). Some of these equations in terms of the flow stress and strain rate are:

$$\bar{\sigma} = \bar{\sigma}_0 \dot{\bar{\varepsilon}}^m$$

$$\bar{\sigma} = \bar{\sigma}_0 + B \ln \dot{\bar{\varepsilon}}$$

where $\bar{\sigma}_0$, B and m are strain and temperature dependent.

In high temperature deformation of metals and alloys the deformation process is thermally activated and often the Zener-Hollomon parameter Z given by

$$Z = \dot{\bar{\varepsilon}} \exp\left(Q/RT\right)$$

is used in the formulation of the mechanical equation of state, where Q is the activation energy, R is the universal gas constant, and T is the deformation temperature.

Careful examination of available hot-working data suggest that the deformation behavior is a balance between strain-hardening and dynamic softening processes (3,4). This behavior led Sellars and Tegart (Ref. 5) to use a more general relation that relates the flow stress, strain rate, and temperature as follows:

$$\dot{\bar{\varepsilon}} = A \left(\sinh \alpha\bar{\sigma}\right)^n \exp\left(-Q/RT\right) \qquad (1)$$

Where A, α, n are materials constants. This formulation ignores the dependency of the flow stress on strain since for most metals at high temperature strain-hardening is very small.

Analysis of the interdependency between stress, strain rate, and temperature--as suggested by the above formulation--gives considerable insight into the mechanism of deformation. The value of the activation energy Q associated with the rate-controlling dynamic softening process indicates the type of deformation mechanism.

In the present study, the above relation was examined. A computer program to carry out the calculation of stress, strain and strain rate at different temperatures, and to determine the materials constant A, α, n and Q in Eq. (1) was developed. The experimental values of stress, strain rates and temperature at different strains in the range of 0.144 to 1.112 are plotted in Fig. 4, and the straight line relationship between Sinh ($\alpha\bar{\sigma}$) and Z using

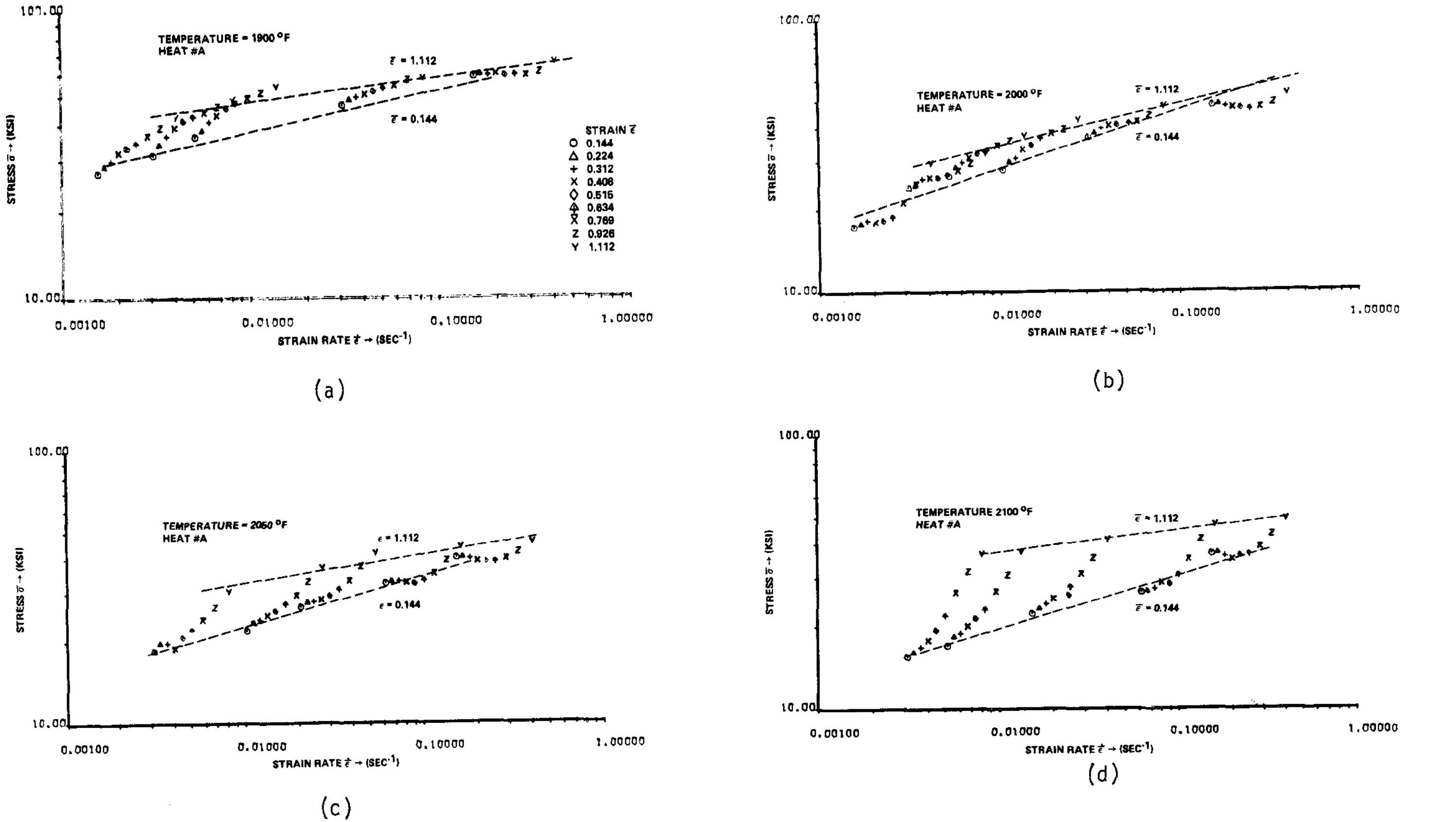

Figure 3. True stress $\bar{\sigma}$ versus true strain rate $\dot{\bar{\varepsilon}}$ at various strains and deformation temperatures

determined values of A, α, n and Q is superimposed. The relationship proposed by Eq. (1) is shown to provide, as first approximation, a fair correlation between flow stress, strain rate and temperature for the Hastelloy alloy C-276. The reason for the scatter is believed to be due mainly to unaccounted strain hardening effect in the formulation of Eq. (1).

The value of activation energ Q for thê high temperature deformation of Hastelloy alloy C-276 was found to be about 109 Kcal/mole. This value is much higher than the value of the activation energy for self-diffusion of Ni ($Q_{SD} \approx$ 66 Kcal/mole) or the activation energy for diffusion in nickel of any of the major alloying elements present in this alloy (6). This could suggest that dynamic recrystallization is the rate controlling mechanism during the high temperature deformation of Hastelloy alloy C-276.

Microstructure Examination

The merger of hot-working tests with examination of microstructural changes associated with the deformation process provide a fruitful insight into the deformation mechanism as well as suggest directions for the control of the quality of the product to meet a specified need. Optical microscopic examinations were therefore done on deformed specimens. The specimens were water-quenched immediately after deformation to retain the microstructure resulting from deformation. Optical micrographs of specimens deformed at various temperatures and speeds are shown in Fig. 5.

Microstructure examination for specimens deformed at 1900° and 2000°F shows uniformly deformed and elongated grains with some nucleation of new recrystallized grains taking place at the grain boundaries. Amount of recrystallization is promoted by higher deformation temperature and speed. Specimens deformed at 2100°F for all speeds and 2050°F for higher speeds show a completely recrystallized and equiaxed fine grain structure with few coarse

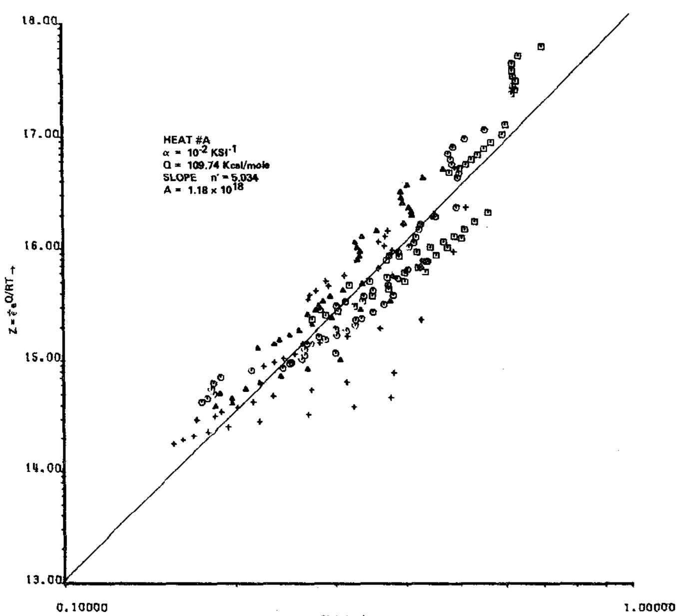

Figure 4 Zener-Hollomon Parameter $Z = \dot{\varepsilon}e^{Q/RT}$ versus $\mathrm{Sinh}(\alpha\bar{\sigma})$.

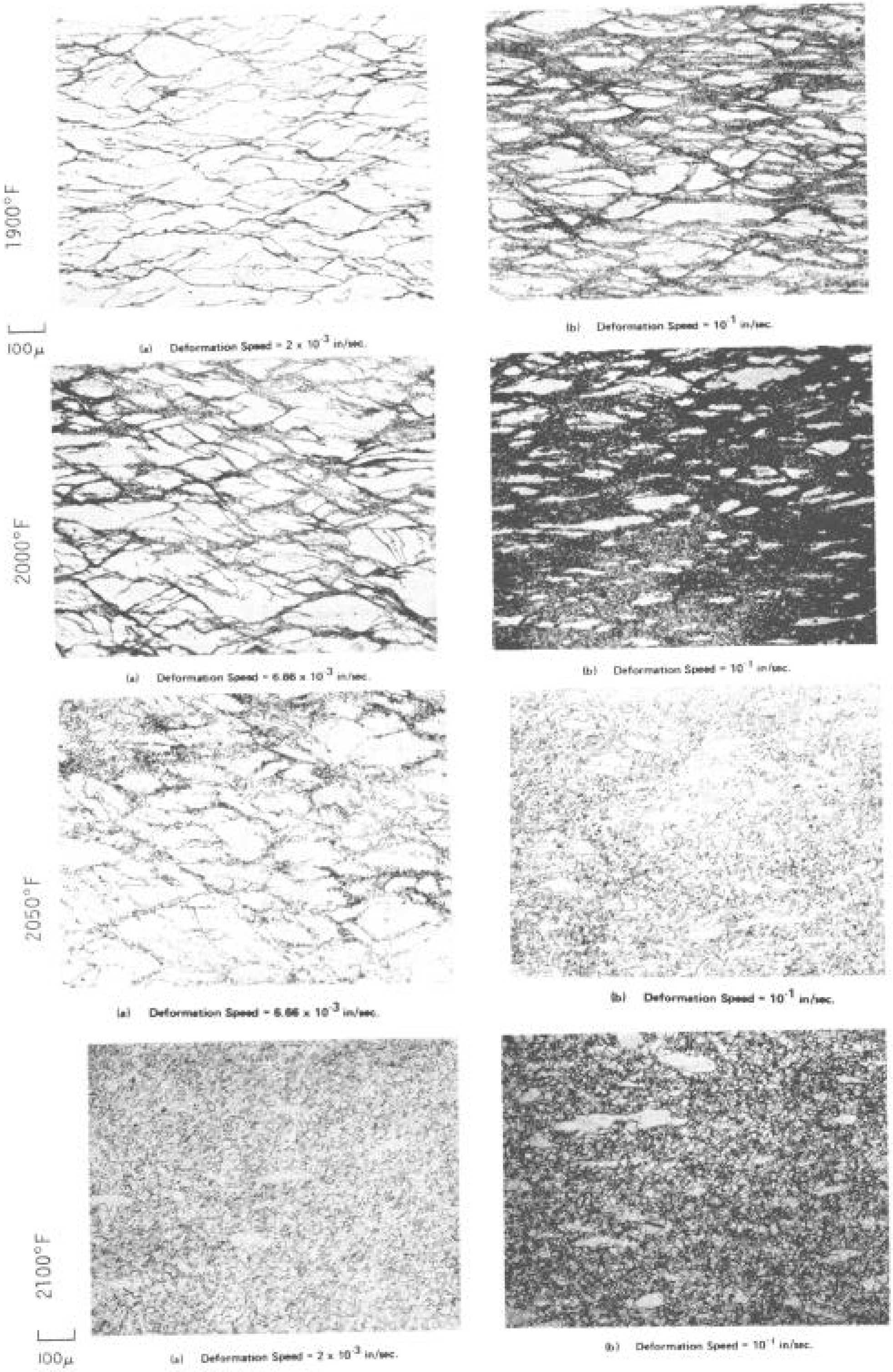

Figure 5. Microstructures of Hastelloy Alloy C-276 deformed at various temperatures and speeds

unrecrystallized grains. Driving force for recrystallization is the amount of energy stored during deformation process which is higher at higher strain rates. It is clearly evident from the microstructure that recrystallization is promoted by both higher speeds of deformation and higher temperature.

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