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An Analysis of Creep in Ni-Cu Alloys

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In two recent creep studies of inhomogeneous nickel-copper solid solution alloys, that is, cast weld metal with solidification-induced composition gradients[1] and nickel–copper laminate composites with controlled composition gradients across the layers,[2] the creep rates at an intermediate temperature (500°C) were shown to decrease with an increase in homogenization. The creep behavior in inhomogeneous alloy systems reflects the composite effects of position–dependent creep properties as controlled by solid solution alloy content. To utilize composite modeling techniques in creep analyses of materials with composition gradients, creep data of homogeneous materials as a function of alloy content are required. Therefore, this study was undertaken to evaluate the creep behavior of nickel-copper solid solution alloys at intermediate temperatures and to provide a base set of data to evaluate the effect of gradients described above.[1,2]

A series of 450g ingots of nickel-copper solid solution alloys with various compositions was produced by melting nickel 270 (> 99.97 pct) and copper C101 (>99.99 pct Cu) in an argon atmosphere furnace. The ingots were homogenized at 1000°C for 12 hours and then hot- and cold-rolled to a final thickness 0f 1.65 mm. These sheets were annealed in vacuum for 1 hour at 700°C for pure nickel and copper and 800°C for the alloys. Tensile specimens with a reduced gage section of $15.9 \times 4.8 \times 1.65$ mm were machined with the tensile axis parallel to the rolling direction. The tensile specimens were creep-tested at 500°C under constant load conditions with an initial stress of 17.2 MPa. All tests were performed on a servohydraulic test system with an attached inert atmosphere glove box[3] which contained the furnace and associated pull-rods. Linear displacement was measured continuously, and the creep tests were carried out until rupture or for a minimum duration of 200 hours. Stress and temperature change creep tests were performed to evaluate the stress and temperature dependence of the minimum creep rates.

Table I lists the alloy compositions, grain sizes, test conditions, and the observed minimum creep rates, $\dot{\varepsilon}$, of the nickel-copper alloys. The creep data are plotted in Figure 1 with nickel atomic percent as the X-axis. Figure 1 clearly reveals that the creep behavior of nickel-copper solid

Table I. Chemical Compositions, Grain Sizes, and Minimum Creep Rates for Nickel-Copper Solid Solution Alloys Tested at 17.2 MPa and 500 °C

Alloy (Aim Comp.)	Actual Nickel Comp. (At. Pct)	Grain Size (μm)	$\dot{\varepsilon}$ (s^{-1})
100Ni	100	57	1.54×10^{-5}
100Ni	100	57	1.26×10^{-5}
85Ni-15Cu	84.3	27	7.50×10^{-8}
85Ni-15Cu	84.3	27	8.10×10^{-8}
70Ni-30Cu	69.0	20	7.20×10^{-8}
70Ni-30Cu	69.0	20	4.90×10^{-8}
55Ni-45Cu	52.2	24	1.00×10^{-7}
45Ni-55Cu	43.1	21	2.31×10^{-7}
45Ni-55Cu	43.1	21	1.70×10^{-7}
30Ni-70Cu	28.6	31	9.33×10^{-7}
30Ni-70Cu	28.6	31	7.36×10^{-7}
30Ni-70Cu	28.6	31	8.06×10^{-7}
15Ni-85Cu	14.6	53	1.48×10^{-5}

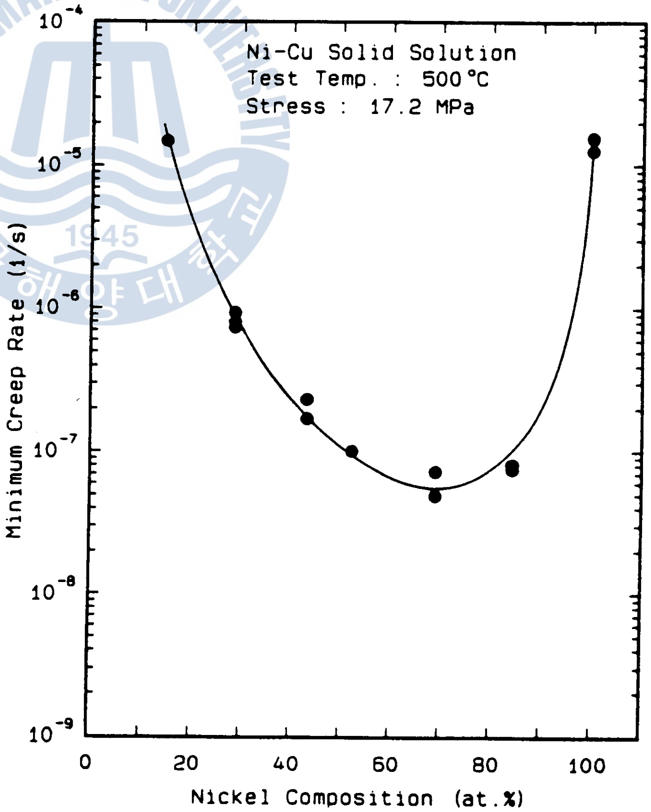

Fig. 1—The relationship between the minimum creep rate and nickel atomic percent for nickel-copper solid solution alloys tested in an argon atmosphere at 500 °C and 17.2 MPa.

solution alloys at 500°C depends sensitively on alloy content. Specifically, addition of either nickel to copper or copper to nickel decreases the creep rate to produce a minimum in the creep rate at a composition of approximately 65 at. pct nickel. In a similar study at higher temperature (727°C to 1000°C), Monma et al.[4] also reported the minimum in the creep rate in the nickel-copper alloy system.

In both the study of Monma et al.[4] and this study, the effects of stress and temperature for each alloy system were evaluated with a unified creep equation of the following form:

$$\dot{\varepsilon} = C\sigma^{n} \exp(-Q_c/RT) \qquad [1]$$

where $\dot{\varepsilon}$ is the steady state or minimum creep rate, σ is the true stress, n is the stress exponent, Q_c is the apparent activation energy for creep, C is a microstructure dependent constant, and R and T have their usual meaning. Figures 2 and 3 plot the minimum creep rates vs stress and inverse temperature, respectively, for data obtained with the stress or temperature change tests. It should be noted that in Figure 1 through 3, all of the experimental data are plotted, and thus, the scatter in

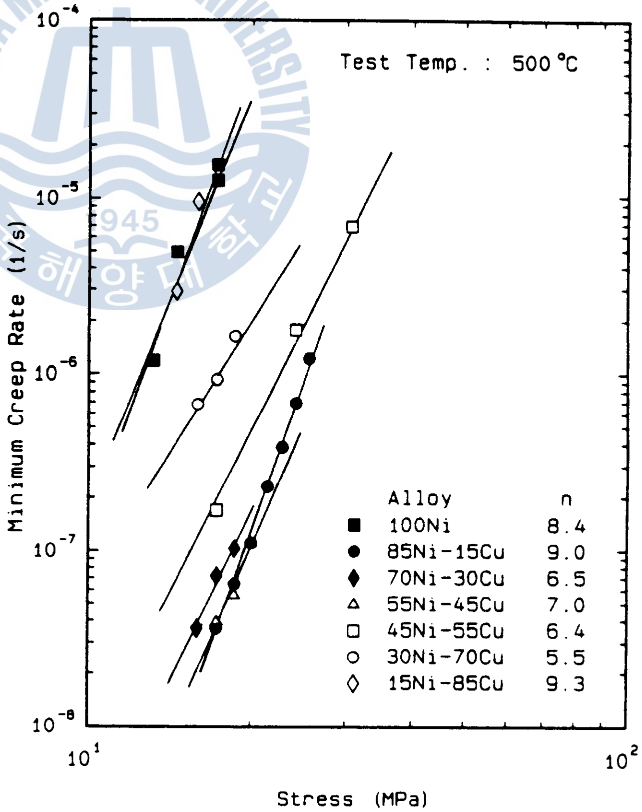

Fig. 2—The effect of stress on the minimum creep rates of a series of nickel-copper solid solution alloys tested at 500 °C. The stress exponents derived according to Eq. [1] are shown.

the data is indicated in the plots.

Figures 2 and 3 show linear correlations for each alloy system, and thus, the values of n and Q_c (as summarized in each figure) were determined as a function of alloy content. In the higher temperature range, the corresponding data of Monma et al.[4] are summarized in Table II. The apparent activation energies for creep for all alloys at 500°C are less than the corresponding values observed by Monma et al., and the stress exponents are higher. Furthermore, a prediction[5] of the creep behavior of nickel-copper alloys at 500°C with the characteristic factors developed by Monma et al. for Eq. [1] showed that the effect of alloy content on the predicted creep rates mirrored that shown in Figure 1, but the predicted rates were five

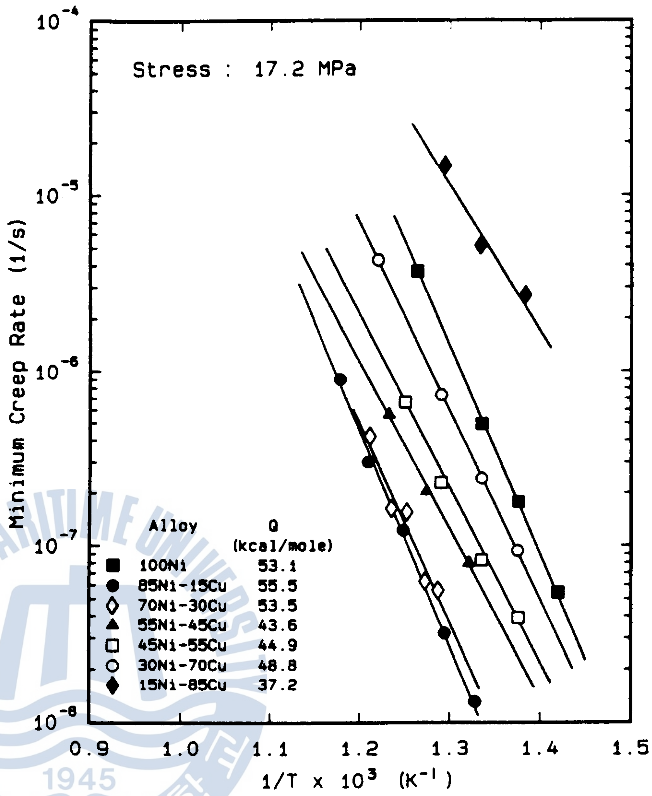

Fig. 3—The effect of temperature on the minimum creep rate of a series of nickel-copper solid solution alloys tested at a stress of 17.2 MPa. The apparent creep activation energies derived according to Eq. [1] are shown.

Table II. Apparent Creep Activation Energies and Stress Exponent Data of Nickel-Copper Alloys at High Temperatures from the Creep Study of Monma *et al.*[4]

Alloy	Composition Cu (At. Pct)	Composition Ni (At. Pct)	n	Q_c (kcal/mole)
Ni	—	>99.95	5.0	66
Ni-15Cu	13.0	bal.	5.1	65
Ni-30Cu	27.9	bal.	5.3	63
Ni-50Cu	45.4	bal.	4.7	61
Ni-65Cu	63.8	bal.	3.8	60
Ni-80Cu	78.5	bal.	4.8	56.5
Ni-90Cu	90.0	bal.	—	45
Cu	>99.9		5.0	42

orders of magnitude lower than observed.

In Table I, grain size variations between 20 and 57 μm were observed for the various alloys of this study. To evaluate the importance of the grain size variations on the data of Figure 1, two alloy systems, 45Ni-55Cu and 30Ni-70Cu, were chosen for further study. Samples of each were annealed at 800°C for 1, 5, and 9 hours to produce grain sizes up to 49 μm. The grain size dependences of the minimum creep rates for these two systems are shown in Figure 4. Both alloys exhibit similar behavior. The minimum creep rates decrease with an increase in grain size up to approximately 37 μm. Above this value, the minimum creep rates are essentially independent of grain size. Therefore, with the observations in Figure 4, which are consistent with the work of Barrett et al.,[6] it is possible to use the following procedure to predict grain size-independent creep rates for each alloy system shown in Table I. First assume that for grain size above 37 μm, the creep rates are grain size-independent for all alloy systems. Then, approximate the behavior illustrated in Figure 4 by two straight lines as shown in Figure 5 for the 30Ni-70Cu and 45Ni-55Cu systems. The lines are parallel in the range where creep rates decrease with an increase in grain

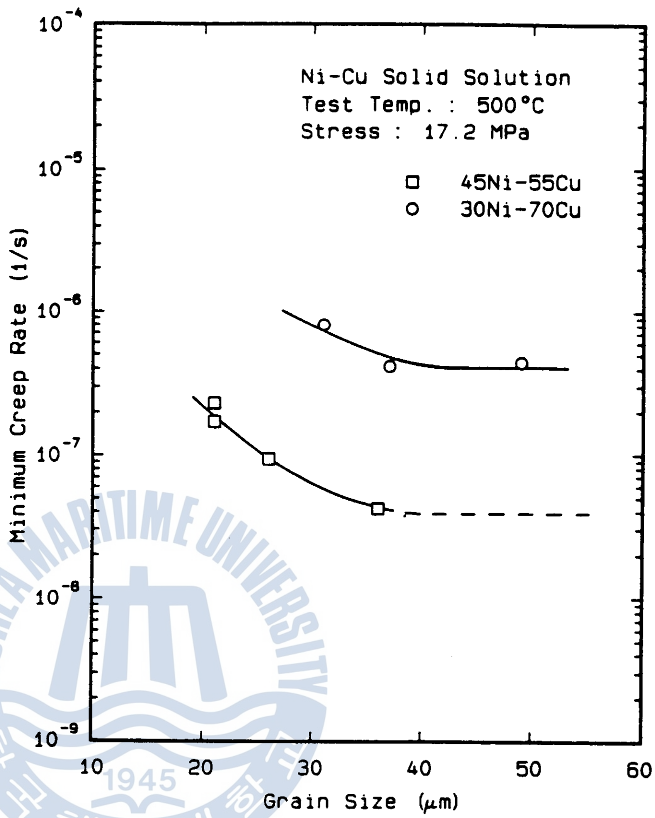

Fig. 4—The relationship between the minimum creep rate and grain size for two nickel-copper solid solution alloys tested in an argon atmosphere at 500 °C and 17.2 MPa.

size. Construct corresponding parallel lines (as shown by the dotted lines in Figure 5) through the grain size-creep rate data for the other alloy systems. Extrapolate these lines to a grain size of 37 μm and read these intercept values as grain size independent creep rates. In Figure 6, the predicted grain size independent creep rates are plotted along with the data shown in Figure 1. The comparison shown in Figure 6 shows that the magnitude of the grain size effect is small in comparison to the effect of alloy content on creep rates.

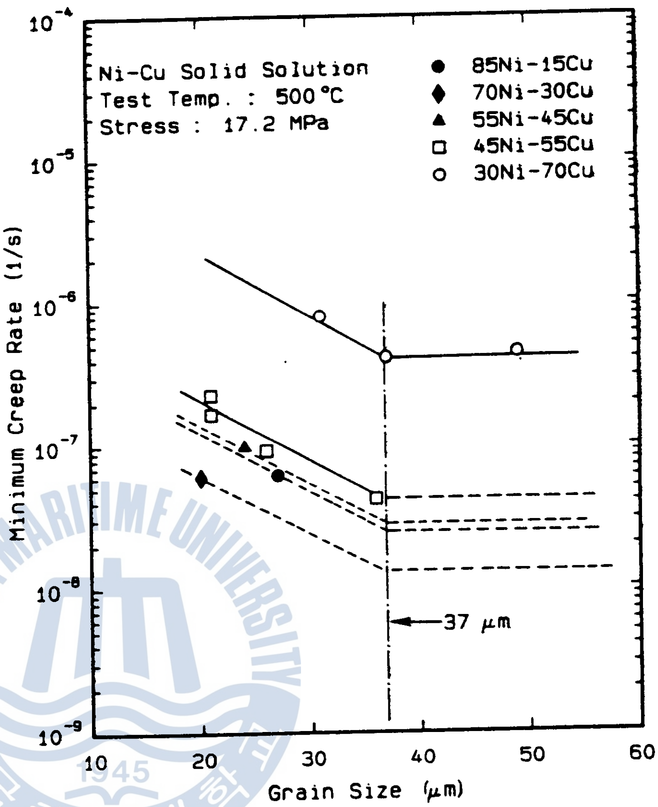

Fig. 5—Extrapolation plot used to determine grain size-independent creep rates for a series of nickel-copper solid solution alloys.

Creep at lower temperatures ($< 0.55T_m$) has been studied in both pure metals and alloys by several investigators.[7−10] Based on analysis of measured creep activation energies, as summarized in Table III along with self-diffusion activation energies and n values, it has been concluded[7−10] that creep at intermediate temperatures is controlled by dislocation pipe (i.e., short-circuiting) diffusion. For example, Norman and Duran[7] investigated the steady-state creep characteristics of pure polycrystalline nickel over the intermediate temperature range 0f 260 °C to 650 °C (0.31 to 0.55 T_m) with stress levels from 46.2 to 248 MPa. The observed Q_c and n values were

41.0± 1.2 kcal/mole and 7.0 ± 0.2, respectively. These values differ from the corresponding values of 66 kcal/mole and 5.0 of Monma et al.[4] in Table II. The decrease in Q_c (see Q_c/Q_{sd} ratio in Table III) and increase in n with a decrease in temperature indicate, based on the analysis of the effects of parallel diffusion processes on creep behavior, that there is a transition from bulk diffusion control at high temperatures to dislocation pipe diffusion control at intermediate temperatures. Therefore, the lower Q_c (Figure 2) and higher n (Figure 3) values for the nickel-copper alloys of this study indicate that creep at 500 °C is controlled by dislocation pipe diffusion.

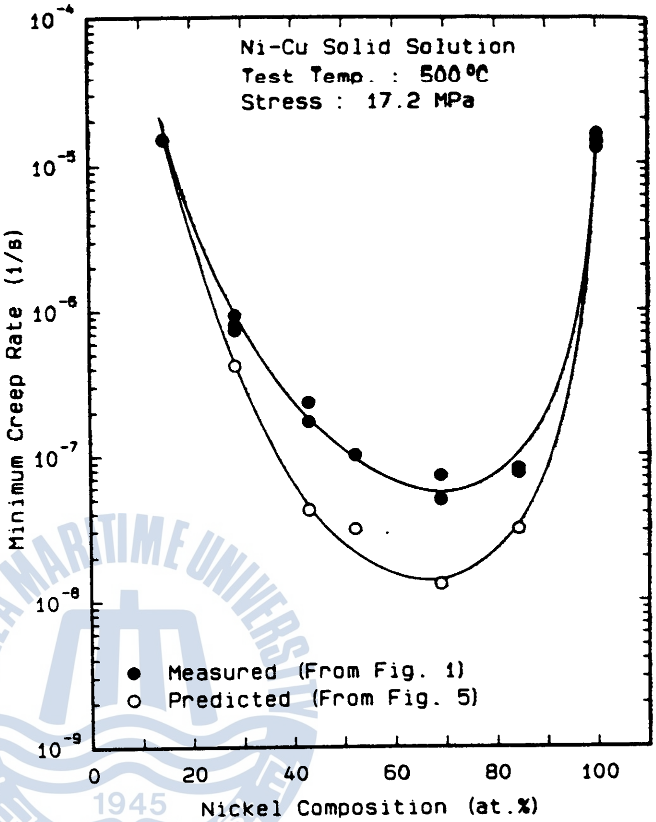

Fig. 6—A comparison of the predicted grain size-independent creep rates with the measured data shown in Fig. 1.

Table III. A Comparison of Creep Diffusion Activation Energies for a Series of Materials Tested at Intermediate Temperatures

Material	Test Temperature (T/T_m)	Q_c (kcal/mole)	Q_{sd} (kcal/mole)	Q_c/Q_{sd}	Reference
Ni	0.31 to 0.55	41	66	0.62	7
Cu	0.5 to 0.65	28	47	0.60	8
W	0.4 to 0.65	90.5	140	0.64	9
Ni-Co alloys (0.1 to 69 wt pct Co)	0.44	43	66*	0.65	10

*Q_{sd} for Ni.

The minimum in the creep rate with alloy content observed both in Figure 1 and in the results of Monma et al.[4] can be interpreted based on the results of Bonesteel and Sherby.[12] Bonesteel and Sherby investigated the influence of diffusivity, elastic modulus, and stacking fault energy on the high-temperature creep behavior of alpha brass. They observed a minimum in the creep rate with solute content. They explained this behavior by noting that the effect of stacking fault energy on creep rate overrides the effects of diffusivity and elastic modulus with solute content. Therefore, it is concluded that the creep behavior controlled by dislocation pipe diffusion at intermediate temperatures is also affected by alloy-dependent properties, i.e., elastic modules, stacking fault energy, and diffusivities, in the same way as the creep behavior controlled by bulk diffusion at high temperatures.

In summary, the creep behavior of a series of nickel-copper solid solution alloys has been quantified at intermediate temperatures and shown to differ from previously reported high-temperature data. These new results have been used in a composite analysis of creep in inhomogeneous systems.[2,5]

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