Some Aspects of Dynamic Restoration Processes in Cu-10Ni Alloy

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Abstract

This paper presents the results of an analysis done on the processes taking place in a polycrystalline Cu-10Ni alloy during deformation in a wide range of temperatures and strain rates. The role of the strain localization on the mechanical performance is a focal point of the analysis.

Using topological (slip line traces) as well as microstructural observations (optical and transmission electron microscopy), the sequence of structural changes has been correlated with mechanical characteristics of the high temperature deformation process in uniaxial compression tests. Two ranges of work hardening were identified on the stress-strain curves, which show a single maxima of flow stress.

Based on observations, the change from a homogeneous into a heterogeneous mode of deformation is caused by evolution of the slip character from fine via a still crystallographically determined transsubstructural coarse slip into a transgranular shear banding. This leads to the division of the metal into periodically active and passive volumes during plastic straining. Within an instantly passive volume (already formed shear bands), there are suitable conditions for nucleation and growth of the recrystallization fronts.

Key Words

Copper-nickel alloy, high temperature deformation, strain localization, dynamic recrystallization.

1. Introduction

Formal theories on dynamic recrystallization based on dislocation density changes and grain boundary migration kinetics /1-3/ as well as models correlating the mechanical characteristics of deformation with the sequence of the structural changes in a wide range of temperatures and strain rates /4-11/ are the results of many years of study.

According to these models which are based on a mechanical /4-7/ or structural criterion /8-11/, the global softening process is interpreted as the effect of the

dynamic recovery (DX) and dynamic recrystallization (DRX) with, in particular cases, the addition of other softening mechanisms such as adiabatic heating, coarsening of precipitates, modification of "hard" textures, and superplastic flow /12,13/.

In some studies, the phenomenon of DRX has been treated as a quasi-homogeneous process characterized by a random distribution of the softening regions in the sample volume /4,14/; other studies, to a smaller or greater extent, emphasize the role of the deformation bands as regions with a considerable deformation gradient and misorientation of the crystal lattice, particularly privileged for nucleation and development of DRX /15,19-21/.

The purpose of the present study is to submit an alternative interpretation of dynamic restoration processes based on an analysis of the reasons for the mechanical instability revealed in the mechanical characteristic of deformation in the Cu-10Ni alloy subjected to high temperature deformation under various thermal and strain rate conditions.

2. Materials

The material used in this study was a polycrystalline Cu-10Ni alloy of the following chemical composition (in wt%): 10.17 - Ni; 1.32 - Fe; 0.001 - Co; 0.78 - Mn; 0.007 - Mg; 0.014 - Zn; 0.002 - Pb; <0.002 - Cd; the rest - Cu.

For the uniaxial compression test, cylindrical samples were used which were 7.9 mm in diameter and 11.9 mm in height and were machined from one rod which was swaged in several passes to reduce its diameter from 15 to 10 mm. The end faces of the samples were grooved to retain the graphite lubricants, which almost completely eliminated friction between the compression anvils and the specimens.

To enable topological observations of deformation (slip marking patterns) which were the only stable elements of the metal "structure" at high temperatures, four flats, 1 mm wide, symmetrically arranged and parallel to the compression axis, were made on the samples' circumferences. Samples prepared in this way

were annealed in a vacuum at 1173 K for 1 h to obtain a stable grain size (D_0) of approximately 55 μm . The flats were mechanically and electrolytically polished for topological observations before the compression tests.

3. Experimental Procedure

Uniaxial compression tests were done on a computer controlled MTS testing machine equipped with a vacuum furnace and a system for cooling the samples. In the temperature range of 898 - 1048 K and at the strain rates range of 0.0005 - 0.05 s^{-1} , the true stress-strain (σ - ϵ) curves displayed flow stress maxima at strains which increased with increasing strain rate and decreasing temperature. In high temperature experiments, particular attention was paid to quenching the samples in order to "freeze" the microstructure, which prevented the progress of static recrystallization or grain growth after deformation. For this purpose, helium gas was used as a quenching medium, which allowed the sample to be cooled within about 1 s.

Topological observations on slip line traces were done using an optical microscope using the Nomarski contrast method. Then the samples deformed to various strains were cut along a plane parallel to the compression axis in order to prepare surfaces and thin foils for microstructural and TEM observations.

4. Results and Discussion

A. Mechanical Behaviour

Figs. 1 and 2 show examples of σ - ϵ curves for different temperature and strain rates. Each curve displays a peak stress in the initial stage of deformation; then the flow stress decreases gradually to a constant value for any deformation condition. The strain to the peak stress shifts to the lower side with increasing deformation temperature or decreasing strain rate.

The character of the metal strain hardening under the given conditions of temperature and strain rate can be described by a number of functions, among which the most useful for the purpose of analyzing strain hardening ranges is the Hollomon equation, $\sigma = K\epsilon^n$, where K is a strength parameter corresponding to the flow stress at

Fig. 1: Effect of deformation temperature at constant strain rate on flow curves of compressed Cu-10Ni alloy. Arrows indicate strain at which steady state stress is first attained.

unit strain, and n is the strain hardening exponent. Just this approximation function was used in the analysis.

Under conditions of high temperature deformation of the polycrystalline Cu-10Ni alloy, two strain hardening ranges were observed which had different values for K and n (Figs. 3 and 4). The first range was characterized by a higher hardening rate ($n_1 > n_2$) and strength coefficient ($K_1 > K_2$) - the end of this range was associated with a change in the nature of the deformation from a homogeneous to a heterogeneous flow [16-21]. Both the values of coefficients K and n and the extent of the range are dependent on temperature and strain rate when the initial grain structure is stable.

Fig. 3 shows that an increase in the deformation temperature results in a decrease in the value of coeffi-

Fig. 2: Effect of strain rate at constant temperature on flow curves of compressed Cu-10Ni alloy. Arrows indicate the strain at which steady state stress is first attained.

coefficients K_1 and K_2 and shifts the boundary between the two ranges ($\epsilon_{1/2}$) to lower strains. Increasing the temperature also leads to an increase in the strain hardening coefficient associated with the first range of n_1 and to a decrease in the values of the strain hardening coefficient of the second range of n_2 .

Changes of similar character were observed when the strain rate was increased under conditions of constant deformation temperature (Fig. 4). In this case, coefficients K_1 , K_2 , and n_2 again decreased, and the boundary between the strain hardening ranges ($\epsilon_{1/2}$) was shifted towards lower strain values whereas strain hardening coefficient n_1 was increased as before.

As expected, values of the peak stress (σ_p), strain to the peak stress (ϵ_p) and the steady state stress (σ_s) show a tendency to increase with decreasing temperature or increasing strain rate. These values and Hollomon's equation parameters as well as values of strain ($\epsilon_{1/2}$) and stress ($\sigma_{1/2}$) between two ranges of strain hardening are summarized in Table 1.

Results of flow stress as a function of the strain rate at seven temperatures were analyzed to calculate the values of activation energy, Q , and stress exponent, n , by using the power law creep relationships, $\dot{\epsilon} = A\sigma^n \exp(-Q/RT)$, in which either the peak stress σ_p or the steady state stress σ_s can be employed. Values of the activation energy, Q , and stress exponent, n , were calculated

Fig. 3: Strain hardening curves for Cu-10Ni alloy deformed at constant strain rate and at various temperatures. Arrows indicate the end of the first range of strain hardening.

Fig. 4: Strain hardening curves for Cu-10Ni alloy deformed at a constant temperature and at various strain rates. Arrows indicate the end of the first range of strain hardening.

Table 1
Summary of Flow Curve Parameters and Hollomon Coefficients

T	σ_p	σ_s	ϵ_p	K_1	n_1	K_2	(data for $\dot{\epsilon} = 0.005 \text{ s}^{-1}$)		
							n_2	$\epsilon_{1/2}$	$\sigma_{1/2}$
[K]	[MPa]	[MPa]		[MPa]		[MPa]			[MPa]
898	216.4	162.2	0.23	327.9	0.267	299.0	0.220	0.14	194.1
923	187.0	139.4	0.18	319.9	0.289	265.8	0.205	0.11	169.1
948	162.9	120.9	0.14	317.1	0.310	233.0	0.182	0.09	150.3
973	142.9	105.5	0.12	305.4	0.317	205.5	0.168	0.07	131.5
998	126.2	92.8	0.10	295.3	0.330	179.5	0.153	0.06	116.7
1023	112.1	82.0	0.09	284.0	0.338	157.4	0.141	0.05	103.2
1048	100.2	73.0	0.08	274.3	0.349	139.1	0.130	0.04	92.9
(data for T = 973 K)									
$\dot{\epsilon}$									
[s ⁻¹]									
0.0005	102.0	72.5	0.08	271.8	0.342	145.3	0.140	0.04	94.1
0.001	112.9	81.2	0.09	274.0	0.326	163.2	0.153	0.05	103.2
0.005	142.9	105.5	0.12	305.4	0.317	205.5	0.168	0.07	131.5
0.01	158.2	118.1	0.13	312.1	0.309	234.5	0.193	0.08	145.7
0.05	200.2	135.5	0.19	335.6	0.288	284.7	0.212	0.12	179.9

from the above relationship with the following results: for $\sigma = \sigma_p$, $Q = 279.7$ kJ/mol and $n = 6.9$; for $\sigma = \sigma_s$, $Q = 259.7$ kJ/mol and $n = 6.2$. These results are comparable to the values given in Blaz et al. [15] and Wierzbinski and Korbel [20], particularly when differences in initial grain size and deformation mode are taken into consideration.

The values of Q permit calculation of the Zener-Hollomon parameter, $Z = \dot{\epsilon} \exp(Q/RT)$, and making comparative analyses of dependences σ_p , σ_s , D_s on $f(Z)$, where D_s is the grain diameter after dynamic recrystallization. The dependence of D_s on the strain rate and temperature is well-known and indicates that D_s is a function of the temperature correlated strain rate or Zener-Hollomon parameter Z [4,15,21]. However, if there is such a relationship, then due to the dependence of the peak and steady stress on Z . A relationship can also be expected between D_s and σ_p or σ_s . Examples of such dependences are shown in Figs. 5, 6 and 7.

B. Microstructure

The analysis of the slip pattern and the structural changes was done on suitably prepared samples subjected

to uniaxial compression at 973 K and a strain rate of 0.005 s^{-1} until the characteristic strain values were obtained.

Fig. 8a shows the surface relief of a sample deformed within the first range of the strain hardening curve ($\epsilon = 0.05$); Fig. 8b shows that of a sample deformed to the extent of the commencement of the second hardening range ($\epsilon = 0.07$); Fig. 8c presents a sample deformed to the middle of the second hardening range ($\epsilon = 0.10$); Fig. 8d shows the surface relief for deformation at the peak stress level ($\epsilon = 0.12$); Fig. 8e shows the surface relief for the strain value corresponding to the middle of the high temperature softening range ($\epsilon = 0.30$); and Fig. 8f shows the surface for the strain value at the level of the beginning of the steady state stress ($\epsilon = 0.50$).

Two families of the deformation band can be distinguished from the topography of the surface. These intersect and pass across the grain boundaries (Figs. 8d, e, f). In some cases, marked strain localization can be observed within particular grains (Figs. 4b and c) as well as different arrangements of slip traces within a single grain resulting from interaction with neighbouring grains (Figs. 8a and b).

Fig. 5: Relationship between peak flow stress (σ_p), steady state stress (σ_s) and temperature compensated strain rate (Zener Hollomon parameter) Z . Activation energy of $Q = 259.7$ kJ/mol was used to calculate Z .

Fig. 6: Relationship between steady state stress (σ_s) and grain size after dynamic recrystallization (D_s) for Cu-10Ni alloy deformed by compression at strain rates from 0.0005 to 0.05 s^{-1} .

Fig. 7: Relationship between grain size after dynamic recrystallization (D_s) and temperature compensated strain rate (Zener-Hollomon parameter) Z . Activation energy of $Q=253.7$ kJ/mol was used to calculate Z .

Fig. 8: Topographic pattern of the homogeneous mode of deformation (a), localized meso (b,c) and macro (d,e,f) scales of polycrystalline Cu-10Ni alloy subjected to compression at 973 K and strain rate 0.005 s^{-1} . (Note: the compression axis is vertical in all the optical micrographs.)

Fig. 9 shows transmission electron micrographs of the samples previously used for the observation of the surface relief. Only dislocation cells (Fig. 9a) were observed in the sample deformed up to $\epsilon = 0.05$.

Families of transsubstructural deformation bands (Fig. 9b) appeared at strain level $\epsilon = 0.10$. The bands formation process became more intense with increasing deformation. Further deformation up to value $\epsilon = 0.35$ was connected with intensifying formation of shear bands (Fig. 9c). On reaching the stress value of the steady flow at $\epsilon = 0.60$, the substructure revealed the occurrence of shear bands and recrystallized grains (Fig. 6d).

These observations indicate that there is a change from a homogeneous mode of deformation (Figs. 8a and 9a) to meso (Figs. 8b, c and 9b) and macro (Figs. 8d, e, f and 9d) strain localization in the course of high temperature deformation. Therefore, the results of the study on the Cu-10Ni alloy led to the same conclusion on the nature of DRX as those drawn from studies of copper [15], nickel [21] and Cu-46Ni [19].

In particular, the change in coefficients K and n as well as the occurrence of the maximum on the σ - ϵ curve are interrelated to the slip organization of the metal. This way of interpreting the phenomenon suggests that the global deformation of the metal is the sum of the homogeneous and heterogeneous deformation (the latter localized in the bands), which finds its reflection in ranges on the strain hardening curve. Similar observations made using TEM and an optical microscope, which point to the development of strain heterogeneity, can also be found in studies done by other researchers [22,23].

The shear, as a potential source of a considerable gradient of deformation and misorientation in the lattice with respect to the matrix, may serve, therefore, as preferential sites for nucleation of static recrystallization within the already passive bands.

5. Conclusions

The above investigations permit us to reach the following conclusions:

- In the process of high temperature deformation of the polycrystalline Cu-10Ni alloy, two ranges occur on the strain hardening curves: the ranges of the homogeneous and heterogeneous deformations, to which the corresponding values of coefficients K and n in the Hollomon equation can be assigned.
- In the case of a stable initial structure, the values of coefficients K and n are determined by temperature and strain rate; a similar tendency for changes was observed with increasing temperature or diminishing strain rate.
- The topological observations show a good correlation between the change in global mechanical characteristics and slip character and distribution in the metal. This clearly shows that activation energy reflects a complex heterogeneous phenomenon. Therefore, based on calculations on global mechanical properties, activation energy is an apparent feature of the deformation process and explains why its value may vary with strain in deformation conditions.
- Evolution of the substructure is characterized by a systematic increase in the density of the deformation bands (shear bands); formation of new grains were not observed until the value of the maximum stress was exceeded.
- The gradient of deformation and misorientation in the lattice in the shear bands causes periodical passivity of the bands from the point of view of their contribution to the global deformation process; this makes then convenient and privileged regions for the nucleation of new grains.
- The investigations show that, in the sequence of structural changes, the shear bands (strain localization) play the most important role in mechanical performance whereas DRX is a secondary phenomenon.

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Fig. 9: Transmission electron micrographs of substructure evolution in samples of polycrystalline Cu-10Ni alloy subjected to compression at 973 K and strain rate 0.005 s^{-1} .

Fig. 9 (continued)

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