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62-930696-17

LA-UR- 93-2290

Title:

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-SOLUTION STRENGTHENED SUPERALLOY**

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Submitted to:

**1993 APS Topical Conference on Condensed Matter
June 28 - July 2, 1993
Colorado Springs, CO**

AUG 05 1993
OSTI

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EFFECTS OF SHOCK LOADING ON A SOLID-SOLUTION STRENGTHENED SUPERALLOY

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Ni-based HAYNES® 230™ ALLOY has been studied to determine the effect of shock loading on the post-shock quasistatic and dynamic mechanical response, and microstructural evolution. The compression properties of this material was studied in both the as-received and shock-loaded conditions at strain rates from 10^{-3} /s to 3000/s, and 77 and 293K. Damage evolution was documented via TEM, and correlated with the observed mechanical response. Changes in the deformation mechanisms and second phase distributions resulting from the shock pre-straining and subsequent testing are correlated with changes in the strain hardening behavior of the materials. Comparison of these results with shock loading results on pure Ni revealed distinct differences in strengthening and defect storage mechanisms.

INTRODUCTION

To date most research on shock-loading effects in FCC materials has been directed at either pure metals or metal alloys strengthened by single element solid solutions or precipitates. Shock-loaded fcc metals and alloys have been repeatedly shown to exhibit increased defect storage, and concurrent higher hardening, behavior in reload tests after shock recovery compared to the same metal deformed at low strain rate to an equivalent strain level[1-3]. By comparison relatively little work has probed the response of more complex, engineering alloys which derive their mechanical properties through a combination of strengthening mechanisms.

In the 1970's and early 1980's a new generation of solid-solution strengthened superalloys was introduced with the goal of approaching the strength of the best cobalt-based alloys, with cobalt additions either reduced or eliminated. An example of this effort, and the subject of the present study is HAYNES® 230™ Alloy (hereafter 230 alloy), which is based on the Ni-Cr-W system. 230 alloy is solid-solution strengthened primarily by tungsten, but like alloy X and cobalt-based HAYNES® 188™ Alloy, also relies to a large extent on carbide precipitation strengthening.

The primary solid-solution element in 230 alloy is tungsten. Tungsten was selected in favor of refractory elements such as molybdenum because of its larger atomic diameter (13%

greater than nickel) and lower diffusivity in nickel. Tungsten also lowers the stacking fault energy (SFE) of nickel thus restricting cross slip of dislocations. Carbides are important contributors to the overall strengthening observed in these alloys, perhaps to a greater degree than solid-solution strengthening.

The purpose of this study was to investigate the effect of shock-loading on the mechanical properties of 230 alloy, and to correlate these properties to the microstructural changes and substructure evolution as a function of strain rate and test temperature.

EXPERIMENTAL PROCEDURE

230 alloy in the form of hot-rolled bar was produced at Haynes International, Kokomo, IN (Heat Number 8305-9-7178). The chemical composition of this alloy is given in Ref. 4, along with the hot-rolling conditions. Shock recovery experiments were performed at New Mexico Tech., Socorro, NM using shock recovery techniques described elsewhere [5]. Samples were explosively shock-loaded to a shock pressure of 55 GPa for a 1.4 μ s pulse duration. Compression samples were EDM machined from the as-received bar stock and shock recovered samples. Compression tests were conducted at strain rates ranging from 0.001 to 3000 s⁻¹, at both room temperature (293K) and liquid nitrogen temperature (77K). Samples for transmission

electron microscopy (TEM) were also sectioned from the recovered samples and observed using a CM-30 operating at 300kV.

RESULTS AND DISCUSSION

Figure 1 shows a TEM micrograph of the starting microstructure of 230 alloy processed at 1121°C. The microstructure consists of grains $\sim 20\mu\text{m}$ in diameter, which contain some annealing twins, large M_6C carbides and smaller M_{23}C_6 carbides. The presence of the annealing twins is indicative of an FCC matrix having a low stacking fault energy, resulting from the W solid-solution addition.

Figure 1. TEM micrograph showing the initial microstructure, particularly the dislocation substructure.

Figure 2 presents plots of the true stress-true strain response of 230 alloy at strain rates of 0.001/s and 3000/s, each at temperatures of 293K and 77K. The most striking aspects of these curves is the strong dependence of the yield strength on strain rate and temperature, as well as the apparent dependence of strain hardening rate on strain rate.

Figure 3 is a TEM micrograph of the as-received 230 alloy following deformation at 77K and 3000/s strain rate. The propensity for coarse planar slip was found to increase with increasing strain rate and decreasing temperature, with the most pronounced example shown here. Following low strain rate-room temperature testing, the dislocation substructure was clearly more homogeneous, although still planar in nature consistent with the low SFE of 230 alloy.

Figure 2. True stress-true strain responses of as-received 230 alloy.

Figure 3. TEM micrograph of as-received 230 alloy deformed at 77K and 3000/s showing planar dislocation arrays.

Figure 4 is a TEM micrograph showing the dislocation substructure and microbands introduced as a result of the shock-loading. The number of microbands varied from grain to grain, and Figure 4 represents a typical density observed; isolated deformation twins were also observed.

Figure 5 presents the reload true stress-true strain response for the shock-recovered 230 alloy material. The material shows a significant increase in yield strength for each test condition compared to the unshocked, as received 230

Figure 4. TEM micrograph of shock-loaded 230 alloy showing dislocation debris and microbands.

alloy. Additional tests were conducted, although not shown, in which compression samples were remachined to remove any slight barreling, reloaded to an additional ~20% strain and the process repeated. In those tests performed at 77K and 3000/s, conducted in the manner described above, 230 alloy exhibited sustained work-hardening to a strength level approaching 2.6 GPa at a true strain of ~1, followed by catastrophic shear failure. At that point, the ratio of flow stress to elastic modulus approaches 1/80.

Figure 5. Reload true stress-true strain responses of shock-loaded 230 alloy.

In general, the microstructures of the reloaded shocked specimens were very similar to each

other, with the reemergence of planar dislocation arrays. The most distinct change in the microstructure from the as-shocked condition was the presence of very fine scale twins. The greatest density of these microtwins was found in the 0.001/s-293K reload sample (see Figure 6). The microtwins were present in almost every grain of this sample, and may explain the reduced hardening rate observed for this sample during the reload tests, see Figure 5.

Figure 7 shows a plot of the quasi-statically loaded stress-strain response of the as-received 230 alloy and the reload stress-strain curve for the shocked 230 alloy. The reload shock curve in Figure 6 has been offset with respect to the as-received 230 alloy response by the transient strain in the shock defined as $4/3 \ln(V/V_0)$, where V and V_0 are the final and initial volumes of 230 alloy during the shock cycle. Also shown in this figure are results from a similar study on pure nickel shocked to 10 GPa [6] showing a significant increase in the reload yield strength compared to the annealed material deformed to an equivalent strain. Contrary to the previous results for pure Ni, Ni-based 230 alloy shocked to 55 GPa does not exhibit an increased shock hardening response compared to the 230 alloy quasi-statically deformed.

Figure 7 also shows the significant increase in strength level on 230 alloy compared to pure Ni, as well as the significantly higher strain hardening rate for 230 alloy, in both the as-received alloy and the shock recovered material. The influence of multiple strengthening mechanisms is clearly evident from the absolute strength levels achieved by these two different nickel-based materials.

Comparison of the influence of shock loading on the mechanical response of pure Ni and Ni-based 230 alloy reveals that the ability to increase the defect storage capacity of each material must be linked to stacking fault energy (SFE) differences. The higher SFE pure Ni is capable of storing a comparatively higher density of defects as a result of the shock loading, than it achieved through normal quasi-static deformation to equivalent strains. In 230 alloy, although the total defect storage capacity is significantly higher than for pure Ni, the amount of hardening achieved by shock loading was no greater than that which would be attained by normal quasi-static deformation. These results suggest that systematic studies of the influence of SFE on

defect storage under shock-loading deformation would be a potentially very insightful avenue for future research.

Figure 6. TEM micrograph of the shock-loaded 230 alloy reloaded at a strain rate of 0.001/s and 293K.

Figure 7. Comparison of as-received and shock-loaded 230 alloy with reload curve of shocked sample offset by transient shock strain. The results from a similar study of pure Ni are also plotted.

CONCLUSIONS

Based on a study of the shock-loading and substructure evolution response of a Ni-based superalloy [HAYNES 230 alloy], the following conclusions can be drawn: 1) substructure

evolution in 230 alloy exhibits planar dislocation arrays which is exacerbated by increasing strain rate and decreasing temperature; and 2) contrary to pure Ni, 230 alloys displays no shock enhanced defect storage due to the low cross slip propensity resulting from the lower SFE due to W alloy additions.

ACKNOWLEDGMENTS

KSV acknowledges support by the U.S. Army Research Office through a URI at UCSD contract #DAAL03-92-G-0108 and GTG acknowledges support by the U.S. Dept. of Energy.

REFERENCES

- [1] G.E. Dieter, in *Response of Metals to High Velocity Deformation*, Interscience Publishers, New York, pp. 409-445 (1961).
- [2] L.E. Murr, in *Shock Waves and High Strain Rate Phenomena in Metals*, (ed. by M.A. Meyers and L.E. Murr) Plenum Press, N.Y., p. 607 (1981).
- [3] G.T. Gray III, in *High Pressure Shock Compression of Solids*, (ed. by J.R. Asay and M. Shahinpoor) N.Y.: Springer-Verlag, ch. 6, (1993).
- [4] K. S. Vecchio, M. F. Fitzpatrick, and D. Klarstrom, submitted to *Metall. Trans.*, 1993.
- [5] Meyers, M. A., L. W. Meyer, K. S. Vecchio, and U. Andrade, "High Strain, High Strain-Rate Deformation of Copper," *Journal De Physique IV*, Colloque C3, suppl. au Journal de Physique III, Oct. 1991, **1**, pp. 11-17.
- [6] P.S. Follansbee and G.T. Gray III, *Int. J. Plasticity*, **7**, pp. 651-660 (1991).

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