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Effects of shock loading on cobalt-based solid-solution strengthened superalloys

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Resumé

Les alliages HAYNES 25TM et 188TM ont été étudiés pour déterminer l'effet du chargement par choc sur la réponse mécanique et l'évolution de microstructure sous rechargements quasi-statique et dynamique. Les propriétés sous compression ont été étudiées pour ces matériaux à leur état initial ainsi qu'à l'état prédeformé par choc. Les vitesses de déformation en compression varient de 10⁻³/s à 3000/s et les températures de déformation sont 77°K et 293°K. Des traitements de recuit à des températures variant de 300°C à 800°C ont suivi le chargement par choc. Pour des températures de recuit en dessous de 600°C, la résistance à l'écoulement plastique sous rechargement et les vitesses d'écrouissage augmentent par rapport aux conditions de choc. L'adoucissement attendu n'a été observé qu'à des températures en dessous de 600°C. Les changements de microstructure, responsables des différences dans les propriétés mécaniques, ont été documentés par l'utilisation du microscope électronique à transmission.

Abstract

Co-based HAYNES[®] 25TM and 188TM alloys have been studied to determine the effect of shock-loading on the post-shock quasi-static and dynamic mechanical response, and microstructural evolution. The compression properties of these materials were studied in both the as-received and shock-loaded conditions at strain rates from 10⁻³/s to 3000/s, and 77 and 293K. Isochronal annealing treatments were conducted at temperatures ranging from 300 to 800°C, following the shock-loading. For annealing temperatures below 600°C, the reload yield strengths and strain hardening rates were found to increase relative to the as-shocked condition, and only at temperatures above 600°C was the expected softening observed. The microstructural changes responsible for these differences in mechanical properties were documented via TEM.

1. 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 complex alloys which derive their mechanical properties through a combination of strengthening mechanisms.

Solid-solution strengthened superalloys such as: HAYNES alloys 188 and 25, derive their strength from a combination of solid-solution additions and carbide precipitation, and can be further strengthened by

cold-working. Shock-loading effects in alloys that exhibit a combination of several strengthening mechanisms and complex microstructures has not been the focus of extensive research to date. However, recent investigations of shock-loading effects in nickel-based superalloys [4], and intermetallics [5] have shown that certain materials exhibit little or no enhanced hardening. The purpose of this study was to investigate the effect of shock-loading on the mechanical properties of Co-based superalloys, and to correlate these properties to the microstructural changes and substructure evolution as a function of strain rate and test temperature. In addition, post-shock annealing treatments were used to investigate the microstructural stability of the shock-loaded materials.

2. EXPERIMENTAL TECHNIQUES

Co-based HAYNES® 25™ and 188™ alloys in the form of hot-rolled bar were obtained from Haynes International, Kokomo, IN to determine the effect of shock-loading on the post-shock quasi-static and dynamic mechanical response, and microstructural evolution. The nominal compositions of both these superalloys are given in Table 1. Shock recovery experiments were performed at New Mexico Tech., Socorro, NM using shock recovery techniques described elsewhere [6]. Samples were explosively shock-loaded to a shock pressure of 49 GPa for a 1.0 μ s pulse duration. The pulse duration of $\sim 1\mu$ s is

defined as: $t_p = \frac{2d_o}{U_s}$, where d_o is the flyer plate thickness and U_s is the shock velocity in the flyer plate.

Compression samples were EDM machined from the as-received bar stock and shock-recovered samples. The compression properties of these materials were studied in both the as-received and shock-loaded conditions at strain rates from 10^{-3} /s to 3000/s, and 77 and 293K. The high strain rate tests were conducted on a split-Hopkinson compression bar. Isochronal annealing treatments were conducted at temperatures ranging from 300 to 800°C, following the shock-loading. Samples for TEM were also sectioned from the recovered samples and observed using a Philips CM-30 operating at 300kV.

TABLE 1
Nominal Chemical Compositions of the Cobalt-based Superalloys

Material	Co	Cr	W	Ni	Fe	Mn	Si	C	La	B
Alloy 25	Bal.	20.0	15.0	10.0	3.0	1.50	0.40	0.10	n/a	n/a
Alloy 188	Bal.	22.0	16.0	22.0	3.0	0.50	0.35	0.10	0.07	0.015

3. RESULTS AND DISCUSSION

Figure 1 shows optical micrographs of the as-received alloys 188 and 25. The microstructures consists of equiaxed grains, which contain annealing twins and M_6C carbides. The optical microscopy of the as-received and the as-shocked conditions did not reveal any significant differences. The presence of the annealing twins in the microstructure is indicative of a FCC matrix having a low stacking fault energy. Deformation twins and microbands were observed as changes in the microstructure of the shock-loaded specimens compared to the as-received condition when examined via the TEM.

The mechanical response of the as-received alloy 25 and alloy 188 at a strain rate of 10^{-3} /s and 3000/s, each at temperature of 293K and 77K are shown in Figure 2(a) and 2(c). 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 2(b) and 2(d) present plots of true stress-true strain response of the shock-loaded alloys 25 and 188. At a fixed temperature and strain rate the flow properties of the shock-loaded alloys are higher than the flow properties of the as-received alloys.

Figure 3 shows the as-received stress-strain response plotted along with the shock-loaded reload curves, with the reload curves offset in strain by the transient strain introduced by the shock. The reload curves for the shock prestrained superalloys in this figure have been offset with respect to the as-received responses at low-strain rate by the transient strain generated by the shock defined as $4/3 \ln(V/V_0)$, where V and V_0 are the final and initial volumes of Co during a 49 GPa shock cycle. The volumes utilized in

Figure 1. Optical micrographs of (a) as-received alloy 188 and (b) alloy 25.

Figure 2. Stress-Strain response as a function of strain rate and temperature for (a) Alloy 25 As-Received, (b) Alloy 25 Shock-Loaded to 49 GPa, (c) Alloy 188 As-Received, and (d) Alloy 188 Shock-Loaded to 49 GPa.

Figure 3. Stress-Strain response comparison between as-received and shock-loaded conditions with the shock-loaded reload curve offset by the calculated transient strain introduced by the shock, (a) alloy 25 and (b) alloy 188.

this calculation assume the equations of state (EOS) response of pure cobalt for both superalloys since the superalloy's EOS's are unknown. The reload curve for alloy 25 shows a small degree of enhanced hardening compared to the level achieved through quasi-static deformation; whereas the reload curve for alloy 188 shows almost no enhanced hardening.

Specimens of shock-loaded alloys 25 and 188 were annealed for one hour at different temperatures ranging from 300°C to 800°C. The room temperature mechanical response of these shock loaded-and-annealed materials were tested at a strain rate of 10^{-3} /s and the reload curves are shown in Figure 4. Low temperature annealing (e.g. 400°C or 500°C) of the shock-loaded microstructures harden the alloys beyond the as-shocked condition as indicated through an increase in the flow curves for these temperatures. At 700 and 800°C, the flow stresses fall below the as-shocked curves as expected from typical annealing treatments. The increase in flow stress with the low temperature anneals is in contrast to what might be expected from conventional annealing effects. To determine whether this effect is due to a "strain-aging" effect or alternatively a "shock" effect, additional specimens of as-received materials were quasi-statically deformed to strains approximately equivalent to the transient shock strains, subsequently aged at either 400 or 500°C, and reloaded quasi-statically. Figure 5 shows the results of these tests, which indicate that these reload curves do not increase in strength following aging, and in the case of alloy 25 shows a clear strength loss.

If a "strain-aging" effect were responsible for the observations in Figure 4, then the reload curves in Figure 5 should have also increased following these annealing treatments. Evidently, other microstructural changes must occur as a result of the shock-loading and annealing; these changes were investigated via the TEM. Figure 6 shows TEM micrographs of alloy 25 specimens shock-loaded + annealed at 400°C (Figure 6(a)), and 700°C (Figure 6(b)). After annealing at 400°C, numerous finely spaced twins appear in the microstructure; similar observations were made at the annealing temperatures of 500 and 600°C, and for alloy 188 as well. The number of these twins was clearly increased over the as-shocked conditions, however the dislocation density appeared unchanged. The finely spaced twins introduced by the low temperature anneals act effectively as grain boundaries, which results in increased strength (i.e. grain refinement), while at the same time maintaining the as-shocked work hardening rates. Following the 700 or 800°C annealing treatments, the twin and dislocation density was significantly reduced, resulting in the observed strength loss, but the increased rate of work hardening.

Figure 4. Stress-Strain response of shock-loaded materials followed by 1 hour annealing at different temperatures between 300°C and 800°C (a) alloy 25 and (b) alloy 188. Note the increase in strength for the annealing temperatures below 700°C, compared to the as-shocked condition. The stress-strain data has been presented only from a true strain of 0.02 so as to allow expansion of the stress data around the yield region.

Figure 5. Stress-Strain response of as-received materials quasi-statically deformed to a strain approximately equal to the strain introduced during shock loading, followed by annealing for 1 hour at 400 or 500°C. Note that this annealing treatment does not result in increased strength compared to the strength of the quasi-statically deformed as-received materials, (a) alloy 25 and (b) alloy 188.

4. SUMMARY AND CONCLUSIONS

Co-based superalloys, HAYNES 25 and 188, have been studied to determine the effects of shock-prestraining on the reload stress-strain response of these materials. It has been shown that shock-loading results in only a minor increase in strength in alloy 25, compared to that achieved by quasi-static deformation, and essentially no enhanced strengthening in alloy 188. Shock-prestraining does however reduce the rate of hardening in both alloys compared to quasi-static hardening rates. Isochronal

annealing treatments were conducted at temperatures ranging from 300 to 800°C, following the shock-loading. For annealing temperatures below 600°C, the reload yield strengths were found to increase relative to the as-shocked condition, and only at temperatures above 600°C was the expected softening and concurrent increase in hardening rates observed. The microstructural changes responsible for these differences in mechanical properties were documented via TEM, and showed that the increase in strength was attributable to fine scaling twinning introduced by the combination of shock-prestraining and subsequent low temperature annealing.

Figure 6. TEM micrographs of alloy 25 following shock-loading and annealing at (a) 400°C and (b) 700°C.

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