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Spall studies in copper foils using the Laser-Driven Miniflyer

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Spalling has been studied in thin (100 to 400 microns thick) copper foil with the laser-driven mini-flyer technique, in which a laser pulse is used to launch a small copper flyer (3 mm diameter by 50 microns thick) against a copper target. Both annealed and heavily cold-rolled copper (99.95+%) have been examined. By controlling the laser energy, and thus the flyer velocity, a full range of spall behavior has been examined, from no damage, to incipient failure, to essentially complete separation. Target back-surface velocities have been recorded by VISAR instrumentation, and the targets have been sectioned and examined metallographically. In the annealed copper, no effect of specimen thickness (100, 200, or 400 microns) was observed. The spall strength of the annealed copper, as estimated from the magnitude of the VISAR pull-back velocity, initially increased as the flyer velocity increased, and then became independent of the flyer velocity over the range examined, at 3 GPa. The spall strength of the cold-rolled copper (100 microns thick) was independent of the flyer velocity, but was much lower than that of the annealed copper, at 2 GPa. Void nucleation in the annealed copper was difficult and infrequent, but no obvious crystallographic or microstructural effects could be discerned. Abundant and homogeneous void nucleation occurred in the cold-rolled copper. Analysis of the VISAR signals provided further insights into the process of void growth and failure. Wave signals corresponding to the thickness of the spall layer could be distinguished at very early times in the VISAR trace, indicating that void formation occurred very early in the failure process.

1. INTRODUCTION

The Laser-Driven Miniflyer (LDMF) is a compact, laboratory-bench-top scale apparatus in which a laser pulse is used for producing high-velocity impacts of small, planar flyers and targets. This device has been constructed at Los Alamos National Laboratory to conduct impact studies of small samples [1-3]. The flyer plates are typically 3 mm in diameter, with a thickness of 50 μm . The targets against which these flyers are impacted are generally about 10 mm by 10 mm in size, with thicknesses from 100 to 400 μm . Flyer velocities in excess of 1 km/s can be attained.

The flyer is positioned on a transparent substrate, one side of which has been coated with vapor-deposited layers of C, Al_2O_3 , and Al, each 0.5 μm thick. The flyer is glued to the outer surface of these layers. The substrate/flyer and the target are assembled into a target holder, with

appropriate spacers between the substrate and the target plate. This target assembly is then placed in a five-axis positioning holder, so that the center of the flyer can be precisely aligned on the optical axis of the laser.

To launch the flyer, a 20-ns pulse from a Nd:Glass laser is directed through the transparent substrate onto the vapor-deposited layers. A special diffractive optical element converts the laser's Gaussian distribution into a top-hat spatial profile, providing a nearly uniform distribution of approximately 80% of the beam's energy over the spot diameter of 3 mm [3]. The laser pulse generates a plasma from the deposited layers which is trapped between the substrate and the flyer. The rapid expansion of this plasma launches the flyer toward the target. The velocity of the flyer can be controlled by adjusting the laser energy with a polarizing attenuator half-wave plate, or by adjusting the laser power supply.

A second laser provides a dual velocity interferometry VISAR (Velocity Interferometry System for Any Reflector) system that monitors the back face of the target throughout the impact event. The VISAR signals are used to interpret the impact process. The dual VISARs provide independent verification of the back-surface velocity measurement, and ensure a self-consistent analysis.

The LDMF offers many experimental conveniences. Sample preparation is simple and inexpensive, since thin, flat specimens are readily fabricated. Testing is rapid, so many specimens can be tested in a short time. Flyer velocities can readily be varied, so a wide range of material responses can be easily examined. The flyer and the target can be recovered after testing for post-test examination. The small specimen size allows testing of materials that are in short supply, or that might be dangerous in larger volumes. However, the small specimen size may result in edge effects, or other complications that need to be considered.

2. EXPERIMENTAL PROCEDURE

Two copper alloys, chemically similar but with very different microstructures, were studied in these experiments. Spall behavior was examined in these model materials by changing the flyer velocity and the target thickness, to aid in characterizing and developing the LDMF technique. In addition, some of these results can be directly compared to data generated on the same material by conventional larger-scale gas gun shots, to examine the effects of specimen size, and the effects of the different pulse duration and strain rate that are present in the LDMF specimens, as compared to the larger gun-shot specimens.

The first copper material was a high purity 10100 alloy (99.995 wt% Cu, 6 ppm S, 7 ppm O, 6 ppm Te), annealed for 1 h at 600°C in vacuum, which resulted in an equiaxed grain structure with a grain size of 53 μm [4]. Slices were cut with a low-speed diamond saw, then ground on both sides on metallographic papers, using a polishing fixture to maintain flatness. Specimen thicknesses of 100, 200, or 400 μm were produced.

The second copper material was commercially available heavily cold-rolled foil, 100 μm thick (Goodfellow Corporation, Berwyn, PA). The reported purity was 99.95+ wt%. The material was

in a "hard temper", and the microstructure consisted of flattened, pancake grains aligned in the direction of rolling. Specimens were cut from the foil.

All specimens were sand-blasted on their back surface with fine abrasive powder prior to testing. This gave a matte finish that minimized specular reflection into the VISARs.

All flyer plates were heavily cold-rolled copper, and were laser-cut from 50- μm -thick foil (Goodfellow Corporation).

Testing was conducted over a wide range of impact velocities, to span the expected material response from no damage, to initial void formation, to complete separation. After testing, the targets were sectioned with a low-speed diamond saw, perpendicular to their thickness, near the center of impact. The sections were mounted edge-on, and polished metallographically to allow the damage in the interior of the specimens to be studied by optical microscopy. Specimens were examined in both unetched and etched conditions.

3. RESULTS AND DISCUSSION

Data from each test were recorded as the back-surface velocity, as measured by the VISAR, as a function of time. These velocity-time curves for each test show a similar form, with a sudden sharp increase in the back-surface velocity that is caused by the compression pulse from the impact of the flyer on the target reaching the back face of the target. Then approximately 23 ns later, a release wave arrives at the back surface, and the velocity abruptly decreases. This time interval is related to the flyer thickness, and the wave speed in the flyer material; it results from the compression pulse from the impact traveling through the flyer, inverting at the flyer free surface, and then traveling back through the flyer, the flyer-target interface, and the target, to reach the target back surface, causing the decrease in the back-surface velocity. For the 50- μm -thick flyers, the 23 ns time implies a wave speed of approximately 4.3 km/s, which is reasonable for Cu. The back-surface velocity then rises and falls as the pulse travels back and forth across the target.

Since all of these tests involved impact of a Cu flyer on a Cu target, the wave speeds in the flyer and the target should be essentially identical,

Fig. 1. Pull-back velocity taken from the VISAR traces plotted as a function of the peak back-surface velocity as measured by the VISAR. This is the same as the impact velocity of the flyer.

although there may be some variation due to the difference between the equiaxed annealed Cu and the very anisotropic cold-rolled Cu. Neglecting such possible minor differences, the peak back-surface velocity measured by the VISAR should be equal to the flyer velocity at impact.

The difference between the peak back-surface velocity and the minimum velocity observed in the first decrease after the peak velocity is typically called the pull-back velocity. The pull-back velocity is shown as a function of the peak back-surface velocity (or flyer impact velocity) in Fig. 1, for all the tests conducted with the annealed Cu (100-, 200-, or 400- μ m-thick specimens) and for the cold-rolled Cu (100- μ m-thick specimens). Several interesting trends can be seen in these results.

The testing clearly distinguishes between the two Cu materials. Initially, at the lower peak back-surface velocities, both materials show an increase in the pull-back velocity as the flyer impact velocity increases. For the cold-rolled material, an

obvious transition occurs at an impact velocity of about 160 m/s, and the pull-back velocity becomes constant at about 110 m/s, and independent of further increases in the impact velocity. A similar, but less dramatic transition occurs for the annealed Cu, with the pull-back velocity increasing up to 140 m/s as the impact velocity increases up to about 180 m/s, and then continuing to increase, but at a slower rate, up to about 170 m/s at an impact velocity of roughly 250 m/s. Above this velocity, the pull-back velocity is independent of the impact velocity.

The magnitude of the pull-back velocity can be used to estimate the spall strength of the material, using the so-called acoustic approach [5] given by

$$\sigma_{\text{spall}} = 0.5 \rho C_o \Delta V \quad (1)$$

where σ_{spall} is the spall strength, ρ is the material's initial density (8.93 Mg/m³), C_o is the bulk wave speed (3.94 km/s), and ΔV is the pull-back velocity. The cold-rolled material has a spall strength of

Fig. 2. A series of VISAR traces for the cold-rolled copper material. At low impact velocities, the waves show a 46-ns periodicity. At intermediate velocities, a 23-ns periodicity is also present. At the higher impact velocities, only the 23-ns-period wave is present.

2 GPa, while the annealed material has a higher value of 3 GPa. These values are calculated above the transition points.

The data for the annealed material show no effect of specimen thickness. The results for the 200- and 400- μm -thick specimens in Fig. 1 are indistinguishable from the results for the 100- μm -thick specimens.

The VISAR traces provide additional information about the impact event and the fracture process. Figures 2 and 3 show a series of the VISAR back-surface velocity traces for 100- μm -thick specimens of the cold-rolled material and the annealed material, respectively, for progressively higher flyer impact velocities. Note that the traces in Fig. 3 have been shifted on the velocity axis for clarity. At the lower impact velocities, the VISAR traces show a periodicity that corresponds to the impact pulse traveling back and forth across the target. Thus, for these 100- μm -thick specimens, a periodicity of about 46 ns is observed. The thicker specimens showed longer periodicities, in

accordance with their increased thicknesses. As the impact velocity increases, a signal can be detected with a periodicity of about 23 ns. This corresponds to the formation of voids at a distance of 50 μm from the back surface. As the impact velocity increases, and the voids that are forming in the specimen become more numerous, and larger, this spall signal becomes more obvious. In this intermediate range of impact velocities, both the 46- and the 23-ns periodicities can be observed. At higher impact velocities, when the voids coalesce and form a nearly continuous open path in the specimen, only the 23-ns-period wave is observed, since the VISAR can only detect the pressure pulse that travels in the layer between the back surface and the spall plane.

The time at which the spall signature, with its 23-ns periodicity, is first observed, can be used to draw some conclusions about the kinetics of void formation. Void growth must be very rapid in these miniflyer tests. The spall signature is seen in the VISAR signal about 30 ns after the first sharp

Fig. 3. A series of VISAR traces for the annealed copper material. Note that the traces have been displaced on the velocity axis for clarity. At low impact velocities, the waves show a 46-ns periodicity. At intermediate velocities, a 23-ns periodicity is also present. At the higher velocities, only the 23-ns-period wave is present.

rise in velocity, which marks the time at which the impact pulse reaches the back surface. If we ignore the elastic wave, and use a wave speed of 4.3 km/s with the spall layer thickness of 50 μm , then the peak tensile stresses would have been attained at about 12 ns after the VISAR sees the initial sharp velocity increase. The spall signal will similarly take about 12 ns to travel from the spall plane to the free surface. Therefore, this implies that the voids take about 6 ns to initiate and grow until they become large enough to create a discernible spall signal. The voids undoubtedly grow over time, so some void formation and growth must occur even sooner than 6 ns after the peak tensile stresses are reached.

Both materials show similar times for the initial appearance of the spall signature (see Figs. 2 and 3), indicating that the kinetics of void formation are similar in these materials, despite the very different microstructures, mechanical properties, and spall strengths. In addition, the nucleation times remain constant for all of the specimens (when void

formation occurs), even as the impact velocity of the flyer increases. Thus, even though the peak stresses are increasing as the flyer velocity increases, the time it takes to create the spall layer remains essentially unchanged.

The fact that the spall signature appears so early in the VISAR trace also indicates that the voids form during the first cycle of high tensile stress, rather than being formed during subsequent stress cycles. If the voids enlarged significantly during later time stress cycles, the spall signature would be initially very small, or even absent, and then strengthen or first appear at later times when the voids were enlarged. The appearance of the spall signature so early in time also indicates that the voids must have been formed early in the impact event, rather than being created or enlarged later on in the process. Furthermore, for tests at the intermediate impact velocities where there is only partial separation of the spalled layer, the 23-ns wave fades in intensity with increasing time, again implying that the voids are not becoming larger and

Fig. 4. Voids in annealed copper specimens. a. Initial stages of void formation. The voids are isolated and spherical. b. Later stage of void formation. Note the linear rows of voids, which are not associated with any obvious features in the microstructure.

more connected at later times. If they were enlarging, the 23-ns wave would strengthen in intensity, rather than fade out.

The metallographic examination revealed that the transition noted in the pull-back velocity response was associated with the first appearance of voids approximately 50 μm from the back surface of the targets, for all target thicknesses. This location is where the reflecting release waves would intersect, since the flyer thickness was 50 μm for all these experiments. The maximum tensile stresses are generated when the reflecting waves intersect and superimpose, so voids are to be expected at this location.

In the first stage of void formation, the voids in the annealed Cu were spherical in shape, infrequent, and usually isolated (see Fig. 4a). No apparent association between microstructural features and the voids could be observed. At higher impact velocities, more voids were present.

Frequently, linear rows of voids were observed, usually lying at some angle to the midplane of the target (Fig. 4b). This linear feature must in fact be a plane or disk of voids, that when sectioned, appears as a row of voids. Again, no apparent microstructural feature could be associated with these rows of voids. Etching the cross-sections showed that the voids did not lie on grain boundaries. Some of the rows of voids appeared to lie parallel to twin boundaries, but many did not. The voids may have formed at particles that all originated from a larger inclusion that was broken up and dispersed during the deformation that the copper material received during its processing. Presumably, the fragments of the initial inclusion would have been spread into a planar array, which resulted in the voids forming a similar pattern. However, the void-forming particles could not be identified, so this remains speculative.

Fig. 5. Voids in the cold-rolled copper specimens. a. Initial stages of void formation. Note the numerous voids distributed about the mid-thickness of the specimen. b. Later stage of void formation. Void coalescence has occurred along the specimen mid-thickness.

Voids in the 200- and 400- μm -thick specimens of the annealed Cu were very similar to those observed in the 100- μm -thick specimens. However, void formation seemed to be retarded in these specimens; that is, for similar flyer plate impact velocities, there seemed to be fewer voids in the thicker specimens than in the 100- μm -thick specimens.

The cold-rolled material showed a much different void-formation behavior. Voids formed abundantly and homogeneously along the mid-thickness of the specimen. At the lower impact velocities, the voids were slightly elongated along the length of the specimen. At higher impact velocities, the voids became more spherical (Fig. 5a). Void coalescence occurred along the mid-thickness of the region containing voids (Fig. 5b). It was not clear whether voids were forming at particles, or at grain boundaries. The severely anisotropic layered structure of the cold-

rolled material made interpretation of the microstructural origins of the voids very ambiguous.

Comparison of the spall behavior of the miniature LDMF specimens with larger conventional gas-gun specimens (4) will help understand the effects of specimen size, pulse duration, and strain rate in these tests. Preliminary modeling with a 1D hydrocode (6) suggests that the spall strength of the LDMF specimens will be higher than that found in gas-gun experiments, for the same material. The calculations predict that voids form at similar stresses in both the LDMF foils and large gas-gun specimens, but can grow to larger sizes in the larger specimens. The sizes of voids found in the present LDMF specimens of annealed Cu are much smaller than the damage observed in the gas-gun specimens of the same material (4). Tests of additional materials by both techniques will help examine these effects.

4. CONCLUSIONS

Miniature impact tests have been conducted with the Laser-Driven Miniflyer apparatus to study spall failure in two chemically similar high-purity copper alloys with very different microstructures (annealed versus cold-rolled). The cold-rolled copper (100 μm thick) had a low spall strength (2 GPa) that was independent of the flyer impact velocity. The specimens showed abundant, homogeneous void formation. The annealed copper had a higher spall strength than the cold-rolled material (3 GPa). The spall strength increased slightly as the flyer impact velocity increased, and then became independent of flyer velocity. No effect of specimen thickness (100 to 400 μm) was observed. Void formation in the annealed material was much less frequent than in the cold-rolled material, and linear rows of voids were often observed, although no apparent microstructural association could be found.

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