LA-UR- 04-5889

*Approved for public release; distribution is unlimited.*

*Title:* MECHANICAL AND SUBSTRUCTURAL RESPONSE OF INCIPIENTLY SPALLED 316L STAINLESS STEEL

*Author(s):* G.T. Gray III (MST-8)

N.K. Bourne, University of Manchester, Manchester, U.K.

*Submitted to:* 11th International Conference on Plasticity

Kauai (Hawaii) January 4-8, 2005

**Los Alamos**
NATIONAL LABORATORY

# MECHANICAL AND SUBSTRUCTURAL RESPONSE OF INCIPIENTLY SPALLED 316L STAINLESS STEEL

**George T. Gray III and Neil K. Bourne***

**MST-8 MS-G755, Los Alamos National Laboratory**
**Los Alamos NM 87544, rusty@lanl.gov**
*** MACE, University of Manchester, PO BOX 88, Sackville Street, Manchester, M60 1QD, U.K., N.K.Bourne@mac.com**

**ABSTRACT-** 316L SS samples were shock prestrained to a peak stress of 6.6 GPa using a 0.75 μsec pulse duration square-topped shock profile and "soft" recovered while a second sample was similarly shock loaded, without spall momentum trapping, leading to incipient spall damage. Shock prestraining and "soft" shock recovery to 6.6 GPa led to an increase in the post-shock flow strength of 316L SS by ~100 MPa over the starting material while the reload yield strength of the incipiently spall damaged sample increased by ~200 MPa. In this paper the sequential processes of defect generation and damage operative during the shock prestraining, spallation, and reloading of incipiently spalled 316L SS is presented.

**INTRODUCTION:** The influence of shock prestraining, using both triangular-wave loading, via both direct HE and triangular-wave pulses on a gas launcher, as well as "square-topped" shock prestaining via conventional flyer-plate impact, is crucial to understanding the shock hardening and spallation responses of materials(Gray III, et al. [2003]). The development of predictive constitutive models to describe the mechanical response of incipiently damaged metals and alloys requires an understanding of the defect generation and storage due to shock hardening as well as the additional plasticity and damage evolution during spallation. In this paper the influence of shock-wave prestraining on the process of shock hardening and thereafter the hardening and damage evolution accompanying incipient spallation in 316L stainless steel (316L SS) on post-shock constitutive behavior is examined using "soft" recovery techniques and mechanical behavior measurements.

**PROCEDURES, RESULTS AND DISCUSSION:** This study was focused on quantifying the influence of incipient spallation damage accrued through square-topped shock loading to a peak pressure of 6.6 GPa on post-shock mechanical behavior of 316L SS. The material used for this investigation was a 316L stainless steel in 12.5 mm-thick plate form. To investigate the influence of incipient spallation damage processes on post-shocked mechanical behavior, 316L SS samples were shock prestrained to a peak stress of 6.6 GPa using a 0.75 μsec pulse duration square-topped shock profile and "soft" recovered while a second sample was similarly shock loaded, without spall momentum trapping, leading to incipient spall damage. 50-mm x 50-mm square (spall) and 38-mm diameter (shock recovery) by 5 mm-thick samples were sectioned from the 316L SS plate. 316L SS samples were shock prestrained to 6.6 GPa using samples fully momentum trapped within "soft" shock recovery assemblies as described previously(Gray III [2000]). Square-topped shock profiles with a pulse duration of ~0.75 μsec were produced utilizing 2.5-mm-thick stainless steel impactors at 350 $ms^{-1}$ so that a central spall plane was introduced in the sample(Gray III, et al. [2003]). The longitudinal stress profiles in the spalled 316L SS samples were measured with commercial manganin stress gauges placed on the rear face of the specimens and supported with thick PMMA blocks(Gray III, et al. [2003]). The spallation response of the 316L SS sample is presented in Fig. 1a showing the "pull-back" signal commensurate with the spallation damage evolved in the sample. The spalled samples and shock-recovery assemblies were deceleration in layers of rags. Specimens for optical metallography were sectioned from the spalled sample.

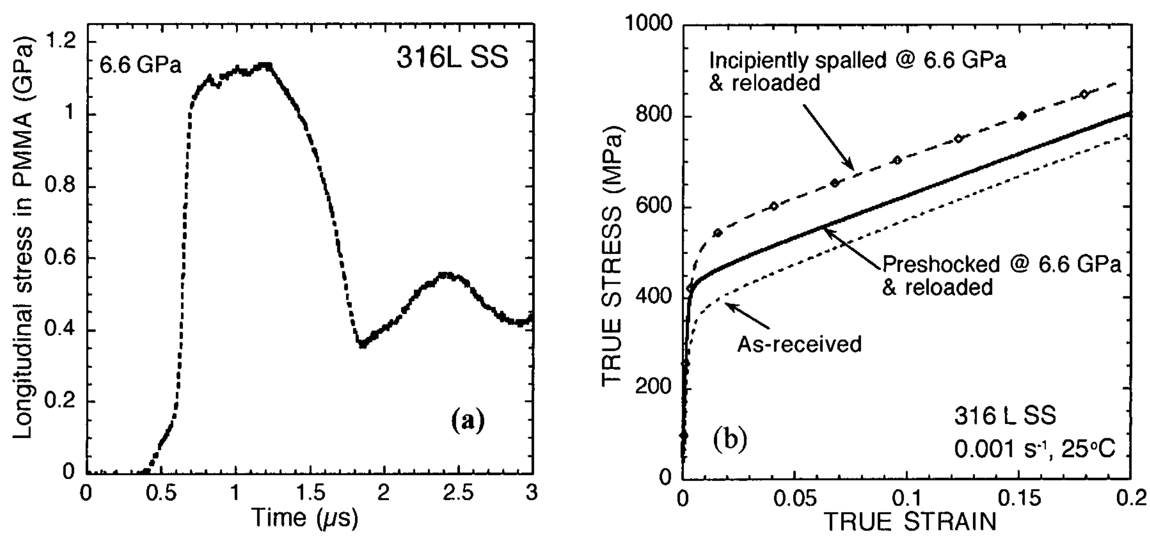


Fig. 1: a) Gauge trace for 316L stainless steel incipiently spalled at a peak pressure of 6.6 GPa, and b) mechanical response of as-received, shock prestrained, and incipiently spalled and reloaded 316L SS .

The post-shock stress-strain responses of the shock prestrained and incipiently spalled samples were quantified by reloading samples electro-discharge machined from the shock-recovered discs and quasi-statically reloaded. The quasi-static stress-strain response of the as-received, shocked prestrained, and incipiently spalled and reloaded samples are presented in Fig. 2b. Shock prestraining and "soft" shock recovery to 6.6 GPa is seen to lead to an increase in the post-shock flow strength of 316L SS by ~100 MPa over the starting 316L SS while the incipiently spall damaged sample yield increased by ~200 MPa. Metallographic examination of the incipiently spalled 316L SS sample loaded to peak pressures of 6.6 GPa was seen to display void coalescence (Fig. 2a). Examination of the incipiently spalled 316L

SS sample following quasi-static reloading to a strain of 0.20 revealed: 1) an hour glass evolution of the cylindrical compression sample shape due to the additional hardening in the spall region resisting plastic flow compared to the remainder of the sample, and 2) the onset of intense slip and shear linkages between the voids formed during spallation (Fig. 2b).

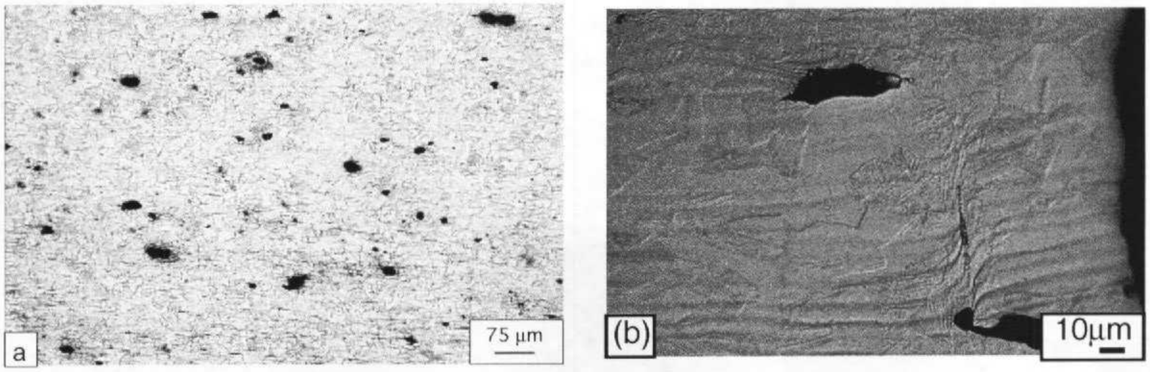


Fig. 2. Optical metallography of: a) inciiently spalled and "soft" recovered 316L SS samples exhibiting ductile voids, and b) shear localization in incipiently-spalled sample following quasi-static reloading.

**CONCLUSIONS:** The current study of the effect of incipient spallation damage on post-shock mechanical and structure evolution behavior of 316L SS reveals that: 1) incipient spallation increases the post-shock yield strength by ~ 200 MPa compared to the ~100 MPa increase due to shock prestraining at a peak shock pressure of 6.6 GPa, and 2) quasi-static compressive reloading of incipiently spalled 316L SS is seen to result in localized plasticity between the ductile voids formed during the incipiently spallation process.

**ACKNOWLEDGEMENTS**: This work was supported under the auspices of the US Department of Energy, specifically in part by the Joint DoD/DOE Munitions Technology Development Program. The authors acknowledge the assistance of G. Cooper for assistance with the spallation testing at the Defense Academy of the U.K.

**REFERENCES:**

Gray III, G. T. 2000, "Shock wave testing of ductile materials", in ASM Handbook. Vol. 8: Mechanical Testing and Evaluation, pp. 530-538, ASM International, Materials Park, Ohio.

Gray III, G. T., Bourne, N. K., Henrie, B. L. and Millett, J. C. F. 2003, "Influence of shock-wave profile shape (triangular - "Taylor-wave" versus square-topped) on the spallation response of 316L stainless steel", J. Phys. IV France, **110**, 773-778.