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# HIGH AND LOW TEMPERATURE DYNAMIC TESTING OF ADVANCED MATERIALS

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A novel experimental research approach that differs substantially from the majority of previous studies is pursued. It consists of performing novel plate impact experiments at low and elevated temperatures. Through variations in temperature, it is possible to study the role of thermal activation on damage and inelastic mechanisms. The technique was used to study variation in the Hugoniot elastic limit (HEL), plastic flow and spallation of Ti-6Al-4V, and to explore thermal activation mechanisms in the formation of the so-called failure waves in soda-lime glass.

#### **INTRODUCTION**

It is well known that temperature plays a crucial role in the viscoplastic behavior of materials under high strain rate, see Johnson (1). However, little research has been done to address the role of temperature on dynamic fracture and spallation, behaviors typically associated with high strain rate failure. Lee and Lin (2) have studied plastic flow and fracture in Ti-6Al-4V by means of a modified Kolsky bar. They explore the range 22-1000°C, and strain rates up  $3000s^{-1}$ . Even if their results are valuable data, they are not easy to model numerically due to the wave propagation assumptions in the Kolsky bar experiment. To successfully model damage and dynamic fracture in Ti-6Al-4V is necessary to characterize the material under well defined deformation conditions, such as the one encounter in plate impact experiments. In this path, Clifton and coworkers (3) developed a technique for pressure-shear experiments at high temperature, and use it to study plastic flow in OFHC copper in the range 300-700°C. Kanel and coworkers (4) studied spall behavior of aluminum and magnesium up to temperatures close to the melting temperature using explosive techniques, and VISAR measurements. To complement this research line, a new experimental technique for plate impact testing of preheated samples was developed and employed to the study the Hugoniot elastic limit, plastic flow and spallation in Ti-6Al-4V in the temperature range 22-300°C, and strain rates of the order of  $10^5 \text{s}^{-1}$ .

Dynamic failure in soda-lime glass is accompanied by a phenomena called failure wave. This phenomena was discovered by Kanel et al. (5) in K5 glasses. Since this, several studies have found similar phenomena in other glasses. Several attempts have been done to uncovered the physical principles that govern the failure wave. Even tough micromechanical models can reproduce experimental results, see Espinosa et al.(6), the physical mechanisms behind the failure wave phenomena is not clear. Kanel et al. (5) argued that a system of microcracks intersecting in space causes the failure wave, Raiser and Clifton (7) proposed two possible mechanisms: a phase





transformation and crack initiation at asperities on the impact surface. By contrast, Espinosa et al. (6) suggested that the inhomogeneous nature of plastic flow in amorphous materials is responsible for the observed damage front. To differentiate these hypotheses, low temperature plate impact experiments were performed. The low temperature is expected to suppress plastic deformation and enhance fracture. Hence, if the failure wave is actually a plastic flow front, pushed by shear stresses generated under a completely compressive state, the damage front kinetics should change dramatically, even disappear.

## EXPERIMENTAL METHOD

The experimental work presented in this paper was conducted in the Dynamic Inelasticity Laboratory at Purdue University. The plate impact facility consists of a 3-inch gas gun, a target vacuum chamber and an interferometric system for recording the transmitted wave profiles. The target chamber is equipped with a sample holder with heating and cooling devices. An induction heating system STATIPOWER LSP12-25/30 (25Kw) coupled with a recirculating heat interchanger LEPEL RWWEX-10 is used to heat up the target assembly. Temperature is monitored by a thermocouple mounted close to the center of the sample. The target sample is glued with high temperature conductive glue to a graphite ring. Afterwards the assembly is placed inside a ceramic sleeve that avoids over heating the induction coil. Ceramic pins keep the sample assembly on position. A copper shield, with circulating liquid nitrogen, is added to reduce heat transfer to the chamber environment and isolate electromagnetic radiation. A remote laser beam is used to monitor specimen tilt, during the heating/cooling process. Corrective maneuvers are applied when necessary. The velocity is measured employing and array of conductive pins. The Ti-6Al-4V samples are lapped to two Newton rings and mirror polished. A platinum coating of approx. 100 nm is applied on the back surface to preserve reflectivity at high temperature. During the target heating, a decrease in Ti-6Al-



FIGURE 1. High temperature Setup

4V reflectivity occurs very fast due to diffusion of the coating in the Ti microstructure and adsorption of oxygen. To keep the laser signal level to a reasonable value a high vacuum (less than 75 mTorr) must be kept at all time.

For low temperature testing a different target holder is employed. It consists of an aluminum ring with a inner channel on which liquid nitrogen circulates. The ring holds the sample by means of copper strips (see Figure 2.) and a backing aluminum ring is placed to increase the heat transfer. The temperature is monitor by means of a thermocouple glued to the specimen. A remote laser beam technique is employed to monitor tilt during cooling. The velocity is measured by a pin array. To avoid laser reflections from the incoming flyer, the glass impact face is covered with black paint. Tilt signal is obtained by depositing a conductive coating on the specimen impact surface using a mask with a special shape. The back surface is coated with a 100 nm layer of gold to enhance surface reflectivity for the VISAR interferometer. A modified VISAR with air-delay leg with a push-pull signal



FIGURE 2. Low temperature setup

processing technique is used to record the wave forms at high and low temperature experiments. In both setups a mirror combined with a 500mm focal length lens is used to collect light for the VISAR. In the high temperature experiments a ceramic cup with a hole is placed in front of the mirror to avoid heating it. Several problems with white light in glass experiments leaded to the addition of a narrow band filter and light intensity monitor in the VISAR setup. In all the experiments a low velocity per fringe (VPF=18.75 m/s) is employed. The wave profile is shifted to match boundary conditions according to Barker (7).

## **RESULTS AND DISCUSSION**

Symmetric impact experiments were performed in Ti-6Al-4V. The target thickness was 7.5 mm with corresponding half thickness for the flyers. A summary is shown in table I. Shot T98-0924, performed at 22°C, represents a reference behavior. First and second loading pulses are observed in the velocity history profile shown in Figure 3. The second loading pulse in this reference shot is greatly attenuated. SEM studies on the recovered target showed that multiple microvoids form in the spall plane position, even thought no clear spallation signal is observed at the end of the first compressive pulse. Based on these observations is possible to say that sig-



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FIGURE 3. High temperature velocity records.

nificant damage at room temperature occurs at stresses lower than the reported spall strength of Ti-6Al-4V ( 5GPa see Me-Bar et al.(9)) Two other shots, shot T98-1210, and shot T99-0602 were performed at about 300°C and different impact velocities. The Ti-6Al-4V alloy presents an HEL of 2.7GPa at room temperature whereas at 300°C it decreases to 2.23GPa, a drop of 18%. Shot T99-0602 reaches a stress at the spall plane (5.75GPa) similar to the spall strength of Ti-6Al-4V (reported in (9)). A reaceleration signal appears immediately after the first compressive pulse in the free surface velocity record. If this signal is interpreted according to Zukas (8), the spall strength at 300°C is 4.75GPa, a drop of 7%. From this results is possible to say that even at very high strain rates thermal softening appears to dominate the deformation process and that the spall strength is less sensitive to temperature than HEL.

Non-symmetric normal plate impact experiments were performed to study the failure wave phenomena. The flyer was a WC/Co plate held in an aluminum holder and backed by a foam spacer, whereas the target is a soda-lime glass plate. A room temperature shot, shot G99-0306 (flyer thickness 3.64mm), was performed to see the kinetics of the failure wave at room tem-





FIGURE 4. Low temperature velocity records.

perature. Similar results to the ones in the literature were found, See Figure 4. The failure wave velocity can be estimated to be 1770m/sec. The second unloading is not sharp as observed in Clifton's work (6), Figure 4.

If the failure wave is generated by shear induced plastic deformation, leading to crack formation, the suppression of plastic flow by lowering the temperature would suppress shear flow and therefore the failure wave phenomena should change. Shot G99-0313 was performed at  $-80^{\circ}$ C (flyer thickness 3.81mm), the measured free surface velocity is also shown in Figure 4. Between the first and second unloading, the trace does not exhibits an increase in axial velocity from the interaction between the unloading front and the advancing failure wave front. From this preliminary results, we infer that failure wave phenom-

**TABLE 1.** Summary of the shot data (T:Ti-6Al-4V, G:Soda-lime Glass).

Shot No	Impact Vel. (m/s)	Normal stress (GPa)	Temp. °C
T98-0924	251	3.48	22
T98-1210	272	3.77	298
T99-0602	417	5.78	315
G99-0313	544	6.97	22
G99-0306	606	7.70	-80



ena is highly connected to thermal activation, in particular to plastic flow. More experiments are required to ensure these preliminary results and allow subsequent successful modeling.

This paper presents a new experimental technique for plate impact testing of preheated or cooled samples. The temperature span goes from -150C to 1000C. The heating facility was used to study variation of Hugoniot elastic limit, plastic flow and spallation of Ti-6Al-4V from room temperature to 300°C at different pressure levels. The cooling facility was employed to explore thermal activation in failure wave in soda-lime glass.

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