Measurement of the Hugoniot curve of Ti-6Al-4V with commercial manganin gauges

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Measurement of the Hugoniot curve of Ti-6Al-4V with commercial manganin gauges

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Abstract. The Hugoniot curve of Ti-6Al-4V was determined in the 0–140 kbar range using calibrated commercial manganin gauges. A two-wave structure was found in all shots corresponding to the elasto-plastic behaviour with a precursor amplitude of about 21 kbar. The Hugoniot curve in the stress–particle velocity curve shows a break around 100 kbar which can be attributed to a dynamic phase transformation. Although no wave splitting phenomena were observed at this stress, the oscilloscope records of the gauges response shows features which can be attributed to the assumed transformation.

1. Introduction

Titanium alloys have received considerable attention in recent years due to their strengths and relatively low densities. Static and dynamic high-pressure studies were focused mainly on pure titanium, beginning with Bridgman's pioneering measurements on the volume and resistance changes up to 100 kbar. Jamieson (1963) indicated a high-pressure phase transformation ($\alpha \rightarrow \omega$) in pure titanium which was later verified by Jayaraman *et al* (1963) using resistance measurements, at about 100 kbar. Subsequent studies, both static and dynamic, reported various values for the phase transformation pressure and values between 50–175 kbar are reported, as summarised by Christman *et al* (1972). These workers made a thorough research of the dynamic properties of α titanium and determined, among other things, the Hugoniot curve for this material. It turned out that a break in the Hugoniot curve near 100 kbar is obtained although no wave splitting was detected.

The aim of the present work was to determine the Hugoniot curve of Ti-6Al-4V alloy in the 0–140 kbar range with the aid of calibrated manganin gauges and to detect the occurrence of a phase transformation. We hoped to observe a multiple wave structure which should have resulted from such a transformation, as was observed in our laboratory for Armco iron (Rosenberg *et al* 1980a).

As was observed by Christman *et al* (1972), no wave splitting occurred in this pressure range and the only evidence for the occurrence of the phase transformation could be inferred from a similar break in the stress–particle velocity Hugoniot curve.

2. Material characterisation

Annealed Ti-6Al-4V plates were used in this study, having density 4·4 g cm^{-3} and hardness 36·5 RC. The microstructure of the material indicates that it has gone through

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considerable mechanical working in the $\alpha+\beta$ temperature region followed by slow cooling, which is the standard mill production procedure. The plates for the high stress experiments were cut from 7 mm sheets and those for the low stress experiments were sawn from a circular billet 250 mm in diameter and then cut to proper dimensions.

3. Experimental techniques

A powder gun 63·5 mm in diameter was used to accelerate planar impactors towards Ti-6Al-4V targets. Measurements of velocity (to 1 %) and tilt of the impact (within 1 mrad) were made by thin coaxial pins which were short circuited by the impactor as described by Oved *et al* (1978). Commercial manganin gauges, manufactured by Micro-Measurements (type LM-SS-125CH-048), were used to determine the stress histories inside the targets. These gauges were calibrated in the 0–180 kbar range using symmetric impacts of materials having well known Hugoniot curves (Rosenberg *et al* 1980b). Thin copper strips (0·01 mm thick) were indium soldered to gauge tabs and served as current leads. Kapton sheets (0·05 mm) served for gauge and lead insulation from the metallic surfaces. A detailed description of gauge encapsulation is given in Rosenberg *et al* (1980b) together with a description of the constant level power supply which monitors resistance changes. These are recorded on dual beam Tektronix 556 oscilloscopes.

Impactor disks made from copper, magnesium and PMMA were accelerated towards the targets with impact velocities in the range of 300–900 m s^{-1} which covered the 10·5–139 kbar stress range. The impactor discs were thick enough (15 mm) so that the first rarefactions to reach the gauge were from the target back surface. Figure 1 shows the experimental set-up at the gun muzzle prior to impact.

The stresses at each experiment were determined with the aid of the calibration curve after which an impedance matching technique was used to determine points of the Hugoniot curve for Ti-6Al-4V. The Hugoniot curves for copper and magnesium were taken from McQueen *et al* (1970) and that of PMMA from Barker and Hollenbach (1970).

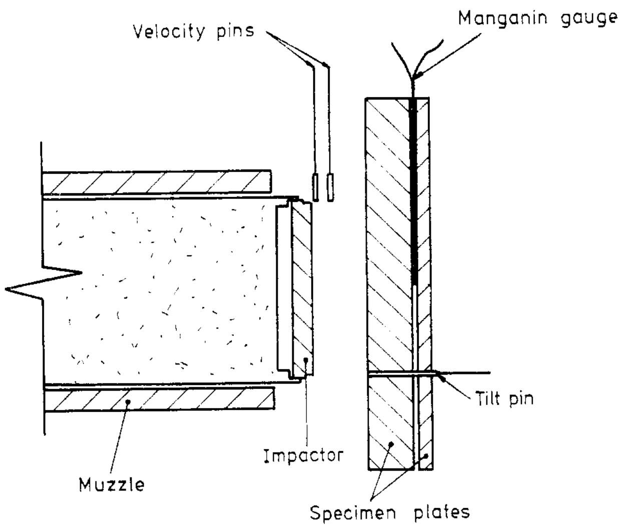

Figure 1. The experimental set-up just prior to impact.

4. Results and discussion

Ten experiments were conducted in this study and the relevant experimental data are given in table 1. A typical oscilloscope record of the resistance change of the gauge is shown in figure 2. One can clearly see the two-wave structure of the oncoming shock with the elastic precursor running ahead of the main plastic shock. This precursor is reflected first from the target back surface and the two-wave structure is also evident in the rerefaction part of the stress pulse.

As seen in figure 2 only two waves were observed in the 0–140 kbar stress range investigated. Thus no indication of a first-order phase transformation was obtained. Such a transformation, occurring dynamically, would have resulted in a further splitting

Table 1. Experimental data.

Shot No.	Impactor material	Velocity (m s^{-1})	Target thickness (mm)		Stress (kbar)
			Front plate	Back plate	
379	Cu	759	6·90	6·88	117
453	Cu	732	14·0	7·0	113·2
460	Cu	755	13·8	7·0	117
479	Cu	895	10·10	6·95	139·0
483	Cu	430	10·10	6·73	65
491	Mg	523	10·15	6·93	33·5
500	Cu	570	10·08	10·08	88·5
515	Mg	331	10·05	10·06	21·5
529	Mg	377	11·85	11·90	24·5
532	PMMA	316	11·90	11·90	10·5

Figure 2. A typical oscilloscope record from a manganin gauge. (Shot No. 460).

of the shock was as found in our laboratory for iron using the same gauges (Rosenberg *et al* 1980a).

The elastic precursor's amplitude varied in the range 21–23 kbar for targets having front plate thicknesses of 14–7 mm. Thus a 2 kbar attenuation of this wave occurred over these thicknesses. This is in good agreement with the attenuation of the elastic precursor found by Christman *et al* (1972) for α titanium although values near 15 kbar were found there for the Hugoniot elastic limit. The difference between these values is probably the result of alloying, which raises both static and dynamic strengths.

The velocity of the elastic precursor was determined by the time duration of the shock level and the back plate thicknesses. This was done for the low stress shots where one can assume that the elastic velocity does not change appreciably even though this wave travels, when reflected from the free surface, into compressed material. Taking minor corrections (due to the epoxy layer thickness) into consideration we obtained a value of $6{\cdot}45 \pm 0{\cdot}1$ mm μs^{-1} from these shots. The plastic wave's velocity is very close to this value even for low stress levels as is shown by the very short time intervals between their arrivals to the gauge planes. A reasonable separation between the two waves was obtained only in the shots with the thick, 14 mm, front plates. The results of this study in terms of the Hugoniot curve for Ti-6Al-4V are shown in figure 3.

It turns out that except for the larger HEL found in this work for Ti-6Al-4V the Hugoniot curve for this alloy and that of α Ti found by Christman *et al* (1972) are very close. Our data points are somewhat higher (larger stresses for the same particle velocity) than those for α Ti. This is expected in view of the higher strength of the alloy.

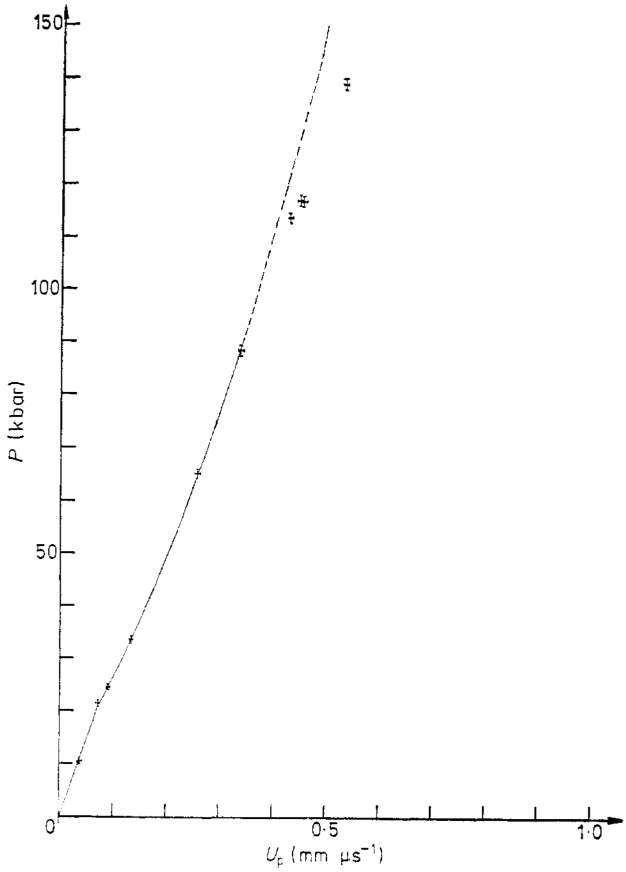

Figure 3. The Hugoniot curve for Ti-6Al-4V.

One interesting feature of the data points in figure 3 is that a small break is seen around 100 kbar. A similar situation was reported by Christman *et al* (1972) where the high stress points (160 and 185 kbar) did not coincide with the extension of the low stress (up to 90 kbar) curve. They argued that this can be an indication for the $\alpha \rightarrow \omega$ phase transformation at about 100 kbar although no further splitting of the wave occurred at the high stresses.

Figure 3 indicates such a break in the stress–particle velocity curve between 88 and 113 kbar. A least square fit to the data points between 21 and 88 kbar extrapolated to the high stress region gives higher points than those obtained in the high shots.

This fit, given by

$$\sigma = 9{\cdot}22 + 148{\cdot}75 U_p + 264{\cdot}82\, U_p^2 \tag{1}$$

gives for example at $U_p = 0{\cdot}45$ mm μs^{-1}, a stress of 129 kbar compared to the 117 kbar obtained experimentally.

Some other interesting features emerge from examining the oscilloscope records for the high stress shots. It is seen that the voltage pulses have a ramped shape at the start of the plastic shock. After some time (typically 1–2 μs) a small decrease in stress is noted, after which the level is fairly constant until back surface rarefactions unload the stress. These features are clearly seen in figure 2. Such behaviour was not found in any other metal we worked with, e.g. copper, magnesium or aluminium.

These features are quite similar to those found by Hayes (1972) for KCl crystals. His explanation for the phenomenon is based on the assumption that the specimen's first response to the shock lies on a metastable extension of the lower phase Hugoniot curve. After some time the material relaxes to the equilibrium Hugoniot curve for the mixed phase region and the stress is lowered. In terms of the stresses which are realised in figure 2, the metastable state is somewhat lower than the extension of the low phase Hugoniot curve, just as was the case for KCl (Hayes 1972).

This behaviour can also explain the fact that no wave splitting was noted by us for Ti-6Al-4V, nor for α Ti by Christman *et al* (1972). However, additional experiments are required to prove that this really is the case, especially near the assumed phase transformation point.

5. Conclusions

Commercial manganin gauges were used to determine the Hugoniot curve of Ti-6Al-4V with the aid of planar impact experiments. An elastic precursor of about 21 kbar was found to precede the main plastic shocks for samples 14 mm thick. There was no further wave splitting which would indicate the usual first-order transformation.

However, a break in the stress–particle velocity Hugoniot curve near 100 kbar is indicative of such a transformation, as was found previously for α Ti (Christman *et al* 1972). The Hugoniot curve obtained in the stress–particle velocity plane is very close to that for α Ti measured by other techniques (Christman *et al* 1972) although a higher HEL was found by us (21 kbar for the alloy against 15 kbar for α Ti). Some additional features of the oscilloscope records point to the possibility of a phase transformation although more experiments are needed, around 100 kbar, to verify this point.

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