# Observation of a two-wave shock configuration in titanium

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The profiles of shock waves in titanium have been measured at pressure amplitudes ranging from 58 to 249 kbar. At 140 kbar, a splitting of the shock wave is observed. This splitting is a consequence of a first-order phase transition. The pressure of the phase transition, which is equal to the amplitude of the first shock wave, is 119 kbar. The velocity of the first shock wave is 5.4 km/s, and the duration of the phase transition is $\approx 0.25\ \mu$s.

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The occurrence of a first-order phase transition during the compression of a solid by a shock wave splits the shock wave and forms a two-wave structure in a certain pressure interval.[1] A splitting of shock waves[1)] has been detected in many materials, and it has been studied in particular detail at the $\alpha$–$\epsilon$ phase transition in iron.[2] In shock waves it is possible to observe the same phase transitions (polymorphic conversions) which occur during static compression. In titanium, however, the two-wave configuration of shock waves has not yet been observed, although the $\alpha$–$\omega$ phase transition was established a long time ago in the static case[3] and has been studied in some detail.[4,5] Furthermore, there are still some uncertainty and differences of opinion regarding the pressure and the identification of the phase transition of titanium in shock waves.

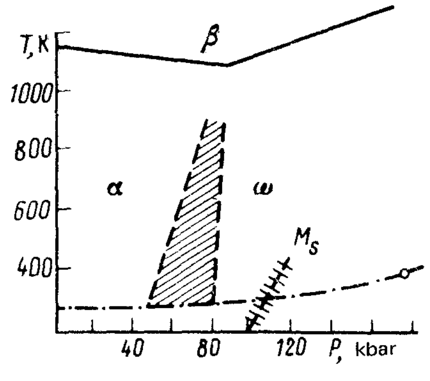

FIG. 1. The *T-P* diagram of titanium. Hatching–Region of the $\alpha-\omega$ phase transition at static pressures[4,5]; dot-dashed curve–Hugoniot adiabat (the circle shows the point of the phase transition) according to Ref. 6. The $M_s$ line is drawn from the data of Ref. 8 and 9.

Figure 1 shows the *T-P* diagram of titanium. The $\omega$ phase forms upon compression to 40-80 kbar (at 300 K), and it persists in a metastable manner after the pressure is removed.[3-5] Measurements in shock waves in this pressure interval have revealed no phase transitions. On the *D(U)* curve, a change in slope has been detected[6] at 175 kbar, but it has been attributed to an $\alpha-\beta$ rather than $\alpha-\omega$ phase transition. After shock waves have propagated through titanium samples, a substantial amount of $\omega$ phase has been observed.[7] A rough estimate of the position of the line at which the $\alpha-\omega$ phase transition begins in shock waves (the line $M_s$ in Fig. 1) has been found from the phase composition of samples recovered from shock-wave experiments.[8,9] From Fig. 1 we find $M_s \approx 110$ kbar at 300 K, while the theory of Ref. 10 predicts $M_s \approx 60$ kbar at this temperature. It is thus particularly interesting

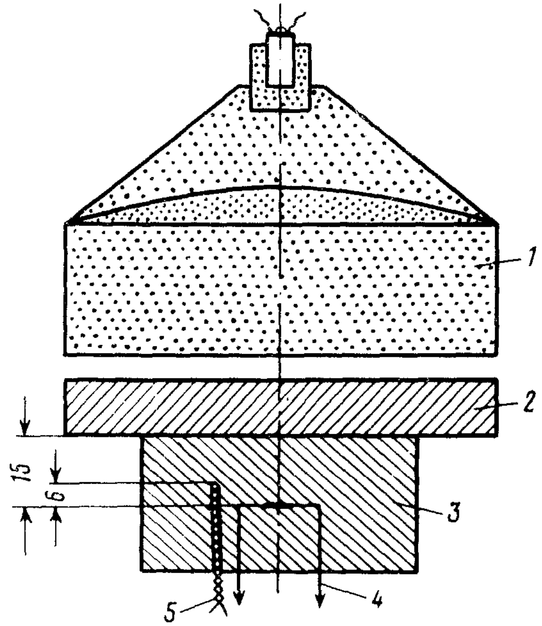

FIG. 2. Experimental arrangement for determining the profile of shock waves in titanium.

to detect the two-wave shock structure in titanium and to directly determine the pressure of the $\alpha$–$\omega$ phase transition; these are the goals of the present work.

The profiles of the shock waves were studied with Manganin pickups.[11] The $\alpha$–$\omega$ phase transition in titanium is accompanied by a comparatively modest change in volume (≈ 1.5%), so that it is difficult to detect the two-wave structure. To improve the accuracy of our measurements, we used S9-4 oscilloscopes as recording devices, and we reduced the distortion inserted by the pickups by reducing the thickness of the pickup and that of the insulating mica layers to 0.02 mm.

The experimental arrangement is shown in Fig. 2. A plane detonation front is arranged in the cylindrical explosive charge 1 with the help of a focusing element, which keeps the front symmetric within 0.05 μs at a diameter of 120 mm. The gap between the explosive charge and the copper or aluminum shield 2 results in a square profile of the shock wave in the shield and in the titanium sample 3. The sample is made of type VT1-0 titanium and consists of two disks each 50 mm in diameter and 15 mm thick. The Manganin pickups 4, which are bifilar spirals 4.5 mm in diameter, are cemented between the titanium disks with epoxy resin. The electrical-contact pickups 5 produce time markers on the oscilloscope traces showing the arrival of the shock wave (*K* in Fig. 3).

The profiles of the shock waves were measured at pressures of 58, 110, 140, 177, 198, 225, and 249 ± 5 kbar. At 58 and 110 kbar, the oscilloscope traces reveal a single-wave shock configuration with an elastic precursor. At 140 kbar (Fig. 3) we see a splitting of the shock wave, which results in the formation of the characteristic two-wave configuration which is evidence of a phase transition. The transition pressure, which is equal to the amplitude of the first, or "loading," shock wave ($P_1$ in Fig. 3), is 119 ± 5 kbar. The front of the second shock wave, with a nominal pressure of 140 kbar ($P_2$ in Fig. 3), is blurred because of the kinetics of the phase transition[1]; from this blurring we can determine the duration of the transition: ≈ 0.25 μs. Between 177 and 249 kbar, the shock wave is again a single-wave configuration without any evidence of a phase transition at 175 kbar (Ref. 6).

We see from Fig. 3 that moving ahead of the steep-front "plastic" shock wave ($P_1$ in Fig. 3) is an elastic precursor1) with a sloping front and an amplitude of 15

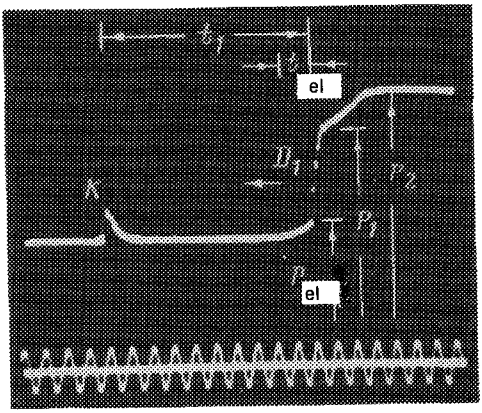

FIG. 3. Oscilloscope trace recorded at a shock pressure of 140 kbar in titanium. The sine wave has a frequency of 10 MHz.

± 5 kbar ($P_{el}$ in Fig. 3). From measurements of the time interval ($t_1$) between the arrival of the shock wave at the electrical-contact pickup and the arrival at the Manganin pickup and from the interval ($t_{el}$) by which the elastic precursor precedes the plastic shock wave (Fig. 3), along with the known distance between the pickups, we can determine the velocity of the first shock ($D_1$) and that of the elastic precursor ($D_{el}$): 5.4 ± 0.1 and 5.9 ± 0.3 km/s, respectively.

In summary, these measurements have yielded the first observation of a splitting of shock waves in titanium due to a phase transition, and the parameters of this transition have been determined. Since the $\omega$ phase appears in titanium after the titanium has been subjected to a shock wave at a pressure[8,9] $\geqslant 100$ kbar, it may be assumed that the two-wave $P_1$ -$P_2$ configuration in Fig. 3 stems from the $\alpha$–$\omega$ phase transition, while the line $M_s$ on the $T$-$P$ diagram (Fig. 1) has a real physical meaning. With regard to the theoretical prediction[10] of 60 kbar as the pressure of the $\alpha$–$\omega$ transition in titanium, it seems that the procedure used for the estimates in Ref. 10 yields values which are too low, since the predicted pressures of the $\alpha$–$\omega$ phase transition are much lower than the experimental values for not only titanium but also hafnium ($\approx 240$ kbar instead of the 500-600 kbar recently found experimentally[12]).

Finally, we should point out that the nature of the slope change on the $D(U)$ curve of titanium[6] at 175 kbar remains an open question and requires further study.[2)] It will also be necessary to determine the position and shape of the $M_s$ line over the entire temperature interval of the $\alpha$–$\omega$ phase transition in shock waves.

[1)] Here and below we mean the "plastic" shock wave, i.e., that with an amplitude above the dynamic yield point ($\approx 18.5$ kbar for titanium[6]), and the splitting of this shock wave due to the phase transition. The elastic precursor leads to an additional splitting of the shock wave.[1]

[2)] After this letter had been prepared for publication, we learned of new data[13] from an unsuccessful attempt to detect the splitting of shock waves at the $\alpha$–$\omega$ phase transition in a titanium alloy. In Ref. 13, in contract with Ref. 6, slight anomalous features were observed on the $P$-$U$ dependence near 100 kbar, in satisfactory agreement with our own results.

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