UDC.669.1:669.3:534:222.2

EFFECT OF SHOCK WAVES ON ARMCO IRON AND COPPER AT DIFFERENT TEMPERATURES*

Z. M. GELUNOVA, V. P. LEMYAKIN and P. O. PASHKOV

Volgograd Polytechnic Institute

(*Received* 14 *August* 1968, *final version* 17 *December* 1968)

The influence of shock waves on pre-heated Armco iron and copper has been studied. Pressures of 115 and 210 kbar at 20-950° were used for iron and 220 kbar at 20-900° for copper. A common property of the metals was found to be a capacity for recrystallization in a certain temperature range at constant pressure. Certain mechanical properties of Armco iron with the various different structures induced by the experiments were measured.

EXPERIMENTAL MATERIALS AND PROCEDURES

Open-hearth Armco iron and copper type M3 were used. The test specimens of Armco iron were 45 × 45 × 7.0 mm in size and those of copper 50 × 50 × 6.5 mm. The specimens were first annealed for 1 hr, the Armco iron at 680 and the copper at 700°. For the Armco iron we used pressures below and above the level necessary for phase transition under normal conditions (130 kbar). The specimen of Armco iron was cooled after the explosion in water, and the copper one in both water and air.

The apparatus used for the experiments is shown in Fig. 1. The specimen 5, in a hot container 6 at the required temperature, is subjected to high-velocity loading by the projection of the percussion plate 4. The HE charge 2 is heat insulated by means of asbestos cover 3. The container, which is at a high temperature, lies on a dry sand bed 7, which prevents the plywood 8 from catching alight. The containers are made of a refractory mixture of fireclay and clay by moulding, drying and roasting. They break as a result of the explosion and the specimen falls through the opening in plate 9 into a thick-walled steel vessel with water 10.

Cooling in water was used so that the conditions should be uniform for all specimens, and also in order to freeze the state of the metal after passage of the shock wave.

The asbestos cover was 15 mm thick. The percussion plate was 50 × 50 × 1.5 mm and was made of steel Ya1T. The distance between plate and surface of specimen was 25 mm. Compressed trotyl was used as the HE. The pressures were calculated for the original cold state according to the formulae proposed in [1] with the use of the adiabatic shock curves of the test metals (plate and target).

Of course, estimating pressures in this way is rather rough, and their values must be regarded as approximate to within ± 10%, which can be checked against known pressure points (e.g. phase transition in iron at 130 kbar) and from the appearance of a highly twinned structure. No special measures were taken to prevent oxidation of the surface during heating because a high surface quality was not required for the subsequent studies. Within the required range of accuracy no further error was introduced to the

* *Fiz. metal. metalloved.*, 28, No. 6, 1064-1069, 1969.

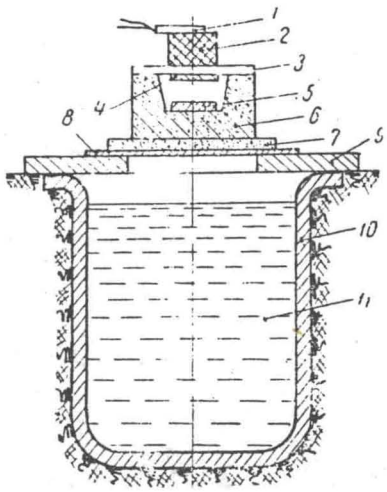

FIG. 1. Diagram of experimental apparatus: *1* - detonator; *2* - HE; *3* - asbestos cover; *4* - percussion plate; *5* - specimen; *6* - warm container; *7* - sand bed; *8* - plywood sheet; *9* - plate; *10* - steel vessel; *11* - water.

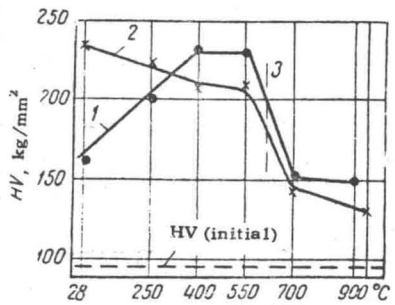

FIG. 2. Temperature dependence of the hardness of iron during shock loading: (*1*) 115 kbar; (*2*) 210 kbar; (*3*) approximate transition point from twinning (left) to granulated uniaxed structure (right).

calculation of the pressures.

The hot container with specimen was loaded into an electric muffle furnace and heated. The temperature in the furnace was checked on a thermocouple. After holding in the furnace at the required temperature the specimen was withdrawn and immediately covered with the asbestos lid. The temperature of each specimen was taken during the shock tests. They reached the explosion position with a temperature 30-40° higher than that required during the explosion. The time taken to cool them ot the temperature necessary for the explosion was determined from a calibration curve. Before the tests the hot asbestos cover was replaced by a cold one with the percussion plate attached to it. There was practically no heat loss.

In the case of high-temperature shock loading (900° or above) the hot container with the specimen was heated in the furnace together with a special refractory cover which had an opening for the thermocouple. After withdrawing from the furnace the temperature inside the container under the lid remained constant for 5 min. The other operations were the same.

RESULTS AND DISCUSSION

From the specimens microsections were made and used for measuring the hardness and analyzing the microstructure. The Vickers hardness was measured across the section of these specimens from the shock surface to the centre where the shock wave can be treated as two-dimensional [3, 8]. In the places where the hardness was measured the deformation of the Armco specimens was not more than 6%, and that of the copper specimens was 8-10%. No measures were taken to prevent plastic deformation in these experiments.

Figure 2 shows the temperature dependence of the hardness of Armco iron specimens under load. The hardness figures were taken at a distance of 0.6 mm from the shock surface.

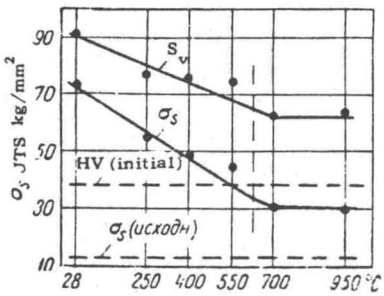

FIG. 3. Mechanical properties of iron vs. temperature during pressure loading at 210 kbar. The vertical line is the approximate transition point from twin (left) to uniaxed structure (right).

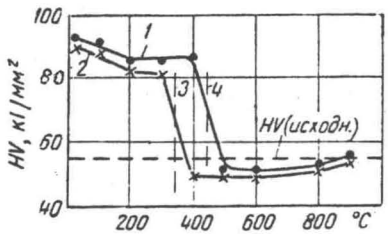

FIG. 4. Hardness of copper specimens vs. temperature during shock loading at 220 kbar:
(*1*) cooled in water; (*2*) in air; (*3*) and (*4*) distinguish the recrystallized (right) from the unrecrystallized (left) structures on cooling in air and water respectively.

The temperature dependence of the hardness obtained for specimens deformed at ~ 115 kbar (curve 1) can be explained by means of the well known [4] phase diagram which relates the phase transition pressure to temperature of iron under the compression of a shock wave in the range -195 to 885°. While iron under these stress conditions is in the α range at 20°, at 250° there is a partial transition to the x range (hexagonal high-pressure phase in iron): this transition is more complete at 400°. Microstructural analysis showed that the intensity of twinning, and accordingly the hardness, rises with the temperature at this pressure.

According to the diagram transition to the γ range should occur at 550°. In specimens stressed at 700 and 900° transition to the γ range actually did occur and was, according to the data of [4], accompanied by recrystallization. The latter involves a considerable reduction in grain size as compared to the original; twin traces disappear and the hardness is diminished.

Curve 2 of Fig. 2 shows the hardness as a function of temperature in specimens under a pressure of ~ 210 kbar. If we allow for the correction to the phase diagram of iron, which consists in raising the boundary between x and γ regions at pressures above 115 kbar [5], then the state in iron at 20, 250, 400 and 550° should correspond to the x phase, and that at 700° to the γ phase. And indeed, twinning was actually found in all specimens stressed in the range of 20-550°. But there was some reduction in the intensity of twinning as the temperature rose, probably resulting in lower hardness [9]. Particularly vigorous twinning and the greatest rise in hardness were observed in iron strengthened at liquid nitrogen temperature (-196°). These experiments were repeated.

In specimens stressed at 700° a recrystallized equiaxed structure was again observed. At 950° the γ-iron resulting from heating was subjected to load. Slight grain refinement as compared with the original was observed.

In Armco iron specimens shock strengthened at different temperatures and a pressure of 210 kbar we determined the resistance to small (proof stress σ_s) and large (true tensile strength S_v) plastic strains using the procedure suggested in [6, 7]. A cone with an angle of 90° at the apex was forced into the polished surface of the specimen on the shock side at a load of 31.25 kg. Then the diameter of the deformed zone D was measured. The yield point was calculated from the formula

$$\sigma_s = \frac{4P}{\pi D^2},$$

where P is the load, kg: D the diameter of the deformed zone, mm. The true tensile stress S_v was determined from the formula

$$S_v = 0.32H_K,$$

where $H_K = \frac{4P}{\pi d^2}$ is the Ludwig hardness (d the diameter of the indentation, mm).

The results are shown in Fig. 3. It can be seen that both the mechanical characteristics fall as the loading temperature rises, but emerge to a constant level at 700°. An interesting fact is that, despite the lack of any essential difference in the grain size of the metal in the initial state and that of strengthening at 950°, it is much stronger. The explanation can probably be found by studying the substructure.

Figure 4 shows the hardness as a function of temperature during stress of copper specimens at ~ 220 kbar. The hardness was taken at a distance of 3 mm from the shock surface. Curve 1 is for specimens cooled in water after the explosion, and curve 2 for those cooled in air. In both cases there is a range of temperature in which the hardness falls rapidly. The range is not the same for different conditions of cooling. The drop in hardness is delayed when cooling occurs in water.

Metallographic analysis of specimens cooled in water showed that, at all loading temperatures right up to 400°, there had been no particular change in microstructure as compared with the original. However, in the specimens loaded at 500° (Fig. 5a) there is considerable grain refinement as compared to those loaded at temperatures up to 400° (Fig. 5b).

The same thing is observed in the specimens loaded at 400° and cooled in air. At higher temperatures there is a gradual increase in grain size; they reach their original size after loading at 800 and 900°. The grain refinement and drop in hardness must be due to recrystallization of the shock-strengthened metal. The structural changes resulting from shock loading Armco iron must be due to phase transitions under pressure. The transition from the α to hexagonal x phase, which is accompanied by a big rise in hardness, has been described a number of times [2, 4, 5, 9]. In this case the grains retain their old boundaries and most of the deformation within them is by twinning. In contrast to this, the α-γ phase transition is accompanied by secondary recrystallization [4]. In our experiments it has been established that the hardness of the recrystallized metal is higher than in the original state, but lower than in the twinned state achieved on the first transformation. Loading in the γ range has caused a very slight change in the grain size and big changes in the mechanical properties of iron.

Copper is not subject to polymorphous transformation as a result of shock loading. But its behaviour is like that of iron subjected to a pressure of 210 kbar. The softening curves have the same shape: in both cases there is a sudden drop in hardness as the pre-heating temperature rises, and this is accompanied by grain refinement. While this is due to phase transformations in iron, such an explanation is not suitable for copper. But total recrystallization also occurs in this metal.

The most logical explanation of this phenomenon is recrystallization of the shock-hardened metal, during the actual process of shock compression. Observations do not contradict this proposition. The drop in hardness and secondary recrystallization of copper cooled in water after deformation occurs at a higher temperature than for those cooled in air (Fig. 4). Since primary recrystallization is a duffusion

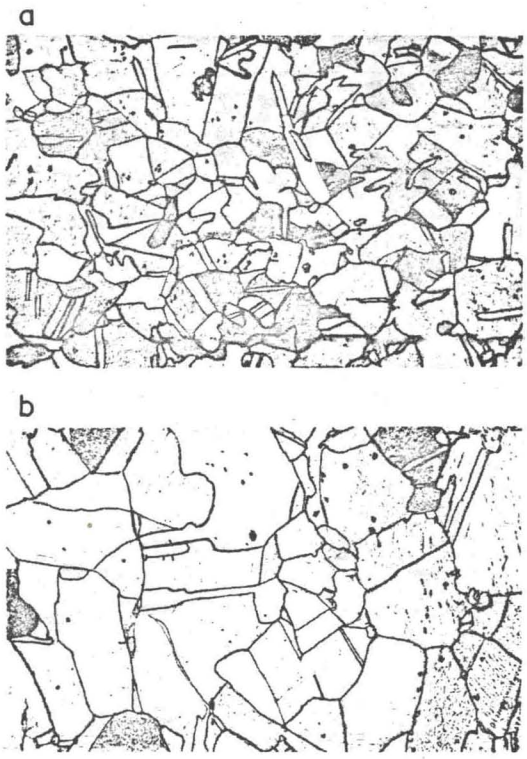

FIG. 5. Microstructures of copper after shock loading at 500° (*a*) and 400° (*b*). Cooling in water; × 100.

process this difference is quite natural, and is evidence of the important part heat stored in the metal plays in deforming it. Grain refinement is also observed at the actual surface of the copper specimen, where cooling is greater than in the centre. The recrystallization must therefore be finished immediately after the shock-wave front has passed, even before the specimen is dropped into the water.

Auxiliary experiments were performed on specimens of commercial-grade aluminium, which underwent big deformations (up to 24%) by shock. The analogous presence of secondary recrystallization was detected when they were microanalyzed.

A peculiarity of the effect of shock waves has been established in [8]. There is a change in the mechanisms of plastic deformation at certain characteristic wave pressures. In particular, for each metal under loading programmes similar to that described above, there exists a pressure at which the velocity of the plastic becomes equal to that of the elastic wave. Under these conditions there arises a characteristic state which is accompanied by loss of lattice stability and is due to the high levels of the instantaneous tangential stresses which have not been successfully relaxed. This state has a close analogy to a phase transition.

In [10, 11] it has been shown that total secondary recrystallization of iron will take place at room temperature under pressures above 670 kbar, where the transition of shock momentum to a single wave structure takes place. Of course, at elevated temperatures the secondary recrystallization should start at a lower pressure, which we were also able to show in this work. A prior rise in temperature is to a

certain degree equivalent to raising the mechanical pressure. In this respect we achieved analogy with mechanical tests for tendencies to brittleness, when lowering the temperature is equivalent to raising the deformation rate.

There is every reason to suppose that deformation conditions like those formulated in [8] have been achieved in the experiments described with copper (and with aluminium if one allows for plastic deformation). A rise in temperature reduces the elasticity of the metal, lowers the yield point and greatly increases the tendency to stress relaxation. A peculiar phase transition of the recrystallization type occurs, relieving the shock hardening and softening the metal despite superficial refinement of the grains. In essence, such treatment is thermomechanical strengthening by shock waves.

CONCLUSIONS

1. On heating to a certain temperature total secondary recrystallization is observed in all the metals tested; it is caused by a high-pressure elastoplastic shock wave and related to the additional rise in the temperature of the compressed metal.

2. Very definite softening is observed in Armco iron and copper in a narrow range of pre-heating temperatures, and it is accompanied by refinement of the grains as compared with the original.

3. As a result of high-temperature thermomechanical shock wave treatment there is a considerable rise in the proof stress, tensile strength and hardness of iron.

4. The phenomena observed can be attributed to the existence of a peculiar form of phase transition at a certain critical pressure.

REFERENCES

1. F. A. Baum, K. P. Stanyukovich and B. I. Shekhter, *Fizika vzryva* (*Explosion Physics*) Moscow, Fizmatgiz (1959).

2. H. B. Dieter, *Sb. Mekh. uprochneniya tverd. tel* (Collection. *Strengthening Mechanisms of Solids*) Moscow, Izd. Metallurgiya (1965).

3. P. O. Pashkov, *Nauchnaya trudi Volgogradskogo Polytekh.* In-ta (1967).

4. P. Johnson, B. Stane and R. Davis, *Dinamich. issled. tverdykh tel pri vysok. davleniyikh* (Collection. *High-Pressure Dynamic Studies of Solids*) Moscow, Izd. Mir, 220 (1965).

5. T. Takahashi and W. A. Basset, *Science*, 145, No. 3641, 483 (1964).

6. N. N. Davidenkov, S. Ye. Belyayev and M. P. Markovets, *Zavodsk. Lab.*, 11, 964 (1945).

7. P. O. Pashkov, *Plastichnost' i razrush. metallov* (*Plasticity and Failure of Metals*) Moscow, Sudpromgiz (1950).

8. V. M. Volchkov, Z. M. Gelunova and P. O. Pashkov, *Fizika i khim. obrabotki meterialov*, 4, 101 (1967).

9. E. S. Atroshchenko, P. O. Pashkov and I. M. Ryadinskaya, *Fiz. metal. metalloved.*, 21, 92 (1965).

10. F. G. Zukas and C. M. Fowler, *Metall. Soc. Conf.*, 9. 343 (1961).

11. V. V. Brazhnev, and Z. M. Gelunova, *Metalloved i prochnost' materialov* (*Metallography and Strength of Materials*) Volgograd. Nizhne-Volzhskoye Izd-vo (1968).