

POTENTIAL OF SHOCK-WAVE METHODS FOR PREPARING AND COMPACTING RAPIDLY QUENCHED MATERIALS

V. F. Nesterenko

Interest in rapidly quenched metal alloys (amorphous, fine- and microcrystalline) is connected with a number of their unique properties; low magnetic losses, high-strength characteristics, corrosion and radiation resistance [1, 2], etc.

In order to obtain amorphous metals is important to have a high cooling rate 10^5 - 10^7 °C/sec), which is achieved as a result of small thickness (10-100 μ m) of the molten metal in contact with a cold substrate [3]. Limitation of one of the amorphous materials dimensions poses the problem of obtaining bulk articles while retaining the amorphous state from tape, powders, etc., which cannot be completely resolved by traditional powder metallurgy methods as a result of the low thermal stability of these material. As a rule their crystallization temperature T_c does not exceed 500-600°C. Bulk specimens of amorphous alloys have been obtained with hot static compaction in a vacuum at a temperature close to the vitrification temperature T_g , e.g., but below T_c [4]. However, the comparatively long time for holding under pressure close to T_g , the necessity of carrying out the process in a narrow temperature range ($T_c - T_g$) close to T_g , and also the limitations on article geometry require development of other methods for compacting amorphous powders.

Features of Shock-Wave Deformation of Porous Materials

The first method by means of which bulk articles have been obtained from amorphous alloy $Pd_{77.5}Cu_6Si_{16.5}$ is explosive compaction [5]. Shock-wave loading methods also make it possible not only to compact amorphous materials, but they may possibly be used for the rapid quenching process itself [6-8]. These types of application for shock-wave deformation are due to the following features.

High Heating Rate. With an increase in temperature ahead of the shock-wave (SW) front by 10^2 - 10^3 °C the heating rate is 10^9 - 10^{10} °C/sec [9-11]. This value is above the rate for the change in temperature in preparing amorphous materials, and therefore with heating in an SW the material will not crystallize.

It is important to note that direct measurement of characteristics connected with temperature is based on the case of porous materials. For these materials a situation is possible when the spatial scale for achieving the final state ahead of the front, close to the equilibrium state, may be different for different parameters, e.g., density and temperature, as in the case of a layered powder model [12].

Nonuniform Warm-Up of Porous Materials. In a number of works using optical methods [13-15] and on the basis of metallographic study of compacts [16-19], zones have been detected with locally increased temperature located along particle boundaries in areas of pore filling. Given in Fig. 1 is the structure of titanium alloy VTZ-1 prepared by explosive compaction of granules with a normal initial temperature and in a vacuum of 10^{-3} Pa. White zones of local heat generation are clearly visible, caused by sliding the particles relative to each other. It is also clear that the temperature of particle contacts and bonds developing between them depends on the nature of their deformation. It is clear from Fig. 1 that the most unfavorable situation for bond formation is quasistatic deformation of a contact with retention of its plane geometry. This situation makes it important to look for criteria of essentially dynamic character for plastic shape-change of powder particles leading to reciprocal sliding in contact areas. One approach to this problem based on comparing the proportion of kinetic energy in the vicinity of pores to energy dissipated during viscoplastic flow is given in [20, 21].

Novosibirsk. Translated from *Fizika Goreniya i Vzryva*, Vol. 21, No. 6, pp. 85-98, November-December, 1985. Original article submitted December 1, 1984.

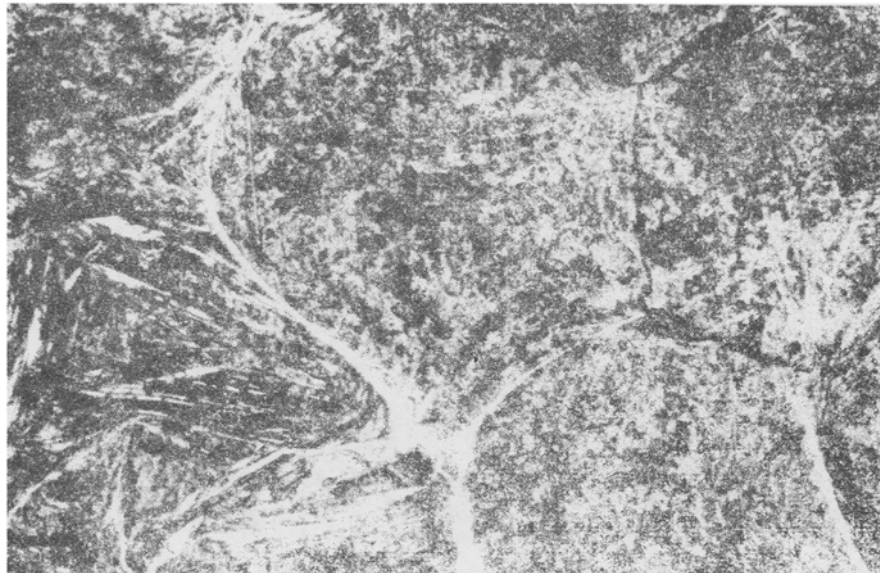


Fig. 1. Dependence of local heat generation on the nature of contact deformation for alloy VTZ-1; $\times 200$.

Using the thermal-emf method a dependence was detected in [9-11] for the nonequilibrium temperature of contacts on fraction size of fractions, to regulate the temperature of particle contacts and to provide the necessary condition for forming strong compacts [22]. In the production pressure region the average temperature of particle contacts for fractions 0.1-0.5 mm may exceed the equilibrium temperature by a factor of two to three [10, 11]. This feature is important for compacting amorphous materials, since it makes it possible by not exceeding $T_c \approx 500^\circ\text{C}$ in the steady equilibrium state ahead of the front, to provide a contact temperature in the front $T_k = 1000-1500^\circ\text{C}$ sufficient to form bonds between particles [23].

High Cooling Rate of Compacts. It was demonstrated in [10] that with an SW pressure $p = 6.5$ GPa the time for temperature relaxation of contacts in powder fractions 0.1-0.5 mm is 5 μsec , which corresponds to a cooling rate of contact zones of $\sim 10^8$ $^\circ\text{C}/\text{sec}$.

The authors of [19, 24-27] conclude that it is possible to reach a cooling rate for the narrow zones along particle boundaries in the range 10^5-10^{10} $^\circ\text{C}/\text{sec}$. These values exceed those within reach for traditional rapid quenching methods. It is necessary to know that the basic assumptions used for analysis in [24-27] are similar to those given previously [15].

In [28] a study is made of contact cooling processes in a periodic system of regions heated to the melting temperature and cold regions, modelling the nonequilibrium condition arising after shock-compression (SC). If the thickness of the molten zone in relation to the size of the powder particle ≤ 0.4 , then during establishment of thermal equilibrium a cooling rate is achieved known to be greater than with preparation of the original amorphous particles by any of the traditional methods.

Thus, in contacting amorphous (microcrystalline) porous materials a significant part of their volume may be converted into a more disordered state than the original particles. The possibility of heating to the melting temperature for a significant part of the material close to particle boundaries may lead to creation of monoliths of quite high strength without loss of the amorphous state.

Breakdown of Oxide Films at Particle Surface. Oxide and carbide films, and nonmetallic inclusions at the surface of granules, during traditional methods of powder metallurgy, e.g., with hot isostatic pressing, as a result of the low value of intragranular shear deformation lead to low strength characteristics for compacts and their sensitivity to stress concentrators [29, 30]. Subsequent plastic deformation promotes breakdown of these surface formations, which in turn accelerates diffusion processes and promoting formation of stable bonds between granules [30].

From this point of view processes of intense shear deformation (see Fig. 1) during shock-wave compaction should have a favorable effect on the breakdown of surface intermetallic inclusions. The importance of this situation as one of the most typical features of dynamic compaction was emphasized in [23].

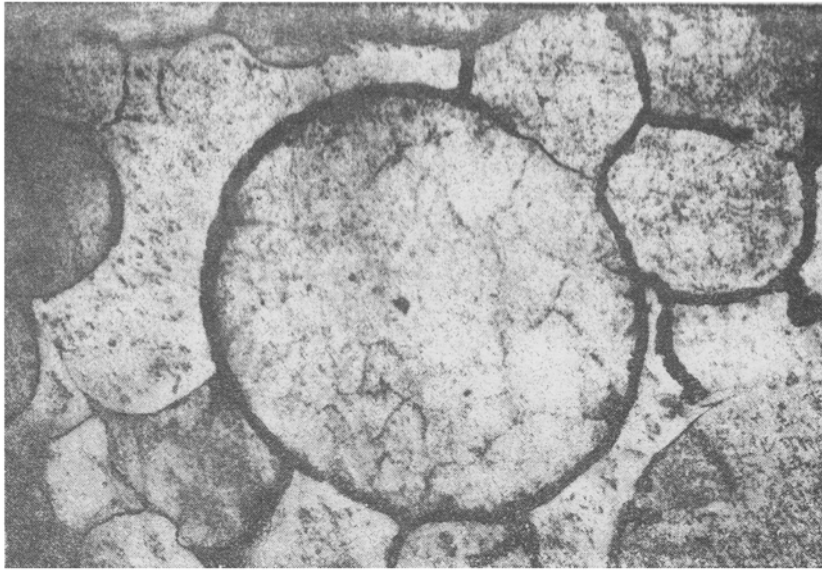


Fig. 2. Nature of deformation for a mixture of granules having different sizes; $\times 200$.

It has been shown in experiments [31] that nonmetallic surface films break down under shock compression in the central part of the front. This means that material compression to the final state occurs at least with partially cleaned contacts. Therefore, their combined plastic deformation may lead to formation of strong bonds.

It should be noted that with quite small fraction sizes and pressure granule deformation during explosive loading has a quasistatic character without purification of their surfaces from oxide inclusions [20]. A criterion was suggested in [20] for changing over from a quasistatic deformation regime to a dynamic regime with a capacity to create particles free from surface contamination.

Dependence of Component Temperature in Porous Mixtures in Material Size Fraction and Properties. It was detected in [10] in a metal and boron nitride mixture that the temperature of the metal component with the same mixture composition, density, and loading conditions, decreases as its size fraction.

It might be expected that if coarse particles of material with a high strength are not in contact with each other in the mixture and they are surrounded by fine particles with low strength characteristics, then all the internal SC energy will be accumulated by the fine fraction. This makes it possible to use SC in order to obtain high-temperature conditions not achievable with loading for a single-component mixture [32]. In particular, this mechanism for achieving a high temperature for one of the components may exist in forming diamond in graphite plus metal mixtures. It is clear that this feature of SC for mixtures of substances may be used in order to melt the component with the fine fraction followed by quenching of the melt due to heat transfer into cold particles of coarse fractions.

An interesting feature is also exhibited for compression of particles of different fractions of the same material. Judging from residual strains for titanium alloy granules (Fig. 2), the main part of thermal energy occurring as a result of plastic deformation is accumulated in the small fraction in this case. The mechanism of the phenomenon may consist of the fact that during contact of particles of different radius high stresses in the loading process initially occur in smaller radius particles. This leads to their plastic flow, warm-up, and further weakening. As a result of this a change in the specific volume of the powder may be achieved by shape change mainly in the smaller fraction. Analysis of the behavior of polydispersed materials is contained in [34].

Strength variation in a mixture of ductile materials also affects redistribution of energy between components [35, 36].

Criteria for Obtaining Strong Compacts

The importance of local processes of heat generation during shock-wave treatment of materials from the point of view of obtaining strong compacts is currently generally accepted.

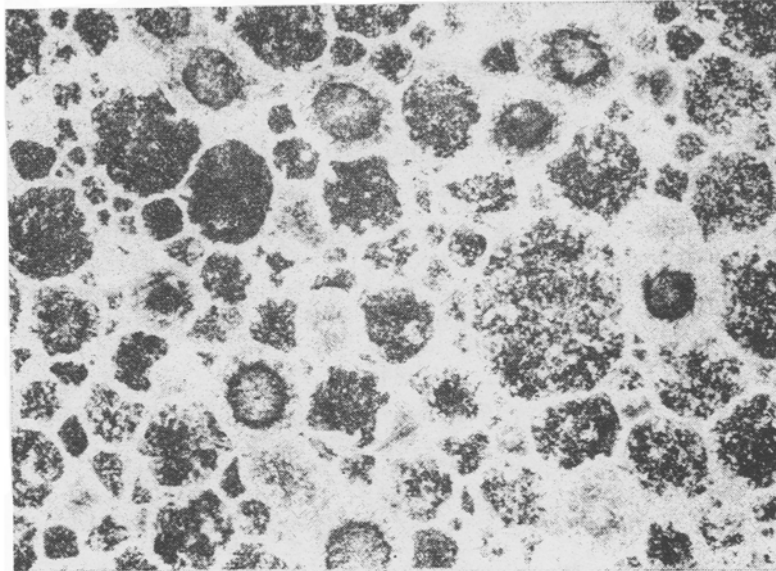


Fig. 3. Structure of a titanium alloy compact for testing with prior heating to 1000°C; $\times 50$.

These processes in turn are governed by particle-size fraction, initial temperature, density, thermodynamic characteristics of the materials, and loading conditions [20-23, 36, 37]. In view of the limited size of the present work there is no discussion of the important problems of preserving articles from crack formation in tensile waves. These questions are considered more completely in [38].

A proposal was formulated in [22] that in order to establish the optimum explosive compaction schedule it is necessary to fulfill the following basic conditions:

$$\varepsilon_0 > \varepsilon_{\min}, p > p_{\min}, E_K > E_{K \min}, t > t_{\min}.$$

Here ε_0 is internal specific SC energy; p , SW pressure; E_K , surface density of specific energy in the contacts; t , SW duration.

The requirement of specifying $E_K > E_{K \min}$ is clearly demonstrated in Fig. 1 where formation of metal bonds can be seen between particles experiencing mutual sliding leading to the required concentration of surface energy for this purpose, and absence of bonds at contacts where simple contortion of particles without marked sliding was observed. Figure 1 clearly demonstrates the situation when a material density is achieved close to the theoretical value, but not providing a bond over the whole surface of particles in contact. More uniform generation of energy over particle surfaces may be obtained, in particular, as a result of prior heating (Fig. 3).

It is noted in [22] that the optimum size fraction lies in the range 0.1-1 mm. This conclusion is based on the fact that as shown by experiment in [9, 10] a size fraction of 0.1-0.5 mm makes it possible to obtain a contact temperature of $\geq 1000^\circ\text{C}$ for powders with a packed density in the pressure region ≤ 5 GPa used in production. In this region it is comparatively easy to provide a loading schedule so that stresses arising during unloading do not lead to specimen failure [38]. It is assumed that surface temperature of this order combined with intense plastic flow and pressure lead to formation of strong bonds between particles. On the other hand, since in actual explosive experiments compressive pulse duration is of the order to 10 μsec with a powder mass velocity of ≤ 500 m/sec, corresponding to this pressure region (≤ 5 GPa), then it is possible to provide the conditions $t > t_{\min}$ by limiting the size fraction to a value of 1 mm.

In contrast to [22], where the requirement $E_K > E_{K \min}$ was proposed, in [24] it was assumed that a strong bond between particles forms on reaching the melting temperature T_S at contacts. A condition for this requirement is:

$$\tau \leq t_m, t_m = 1/12\alpha(a/2 \cdot \Delta T/\Delta T_s)^2, \tau = 3,6a/D, \quad (1)$$

where ΔT_s and ΔT are difference between the melting temperature, the average temperature established ahead of the front, and the initial temperature respectively. It should be noted that whereas the presence of bonds between particle contacts is in fact determined by melting of contact areas, in the criterion for bond formation from ΔT_s there should also be such a parameter as the latent heat of melting. On the basis of these ideas and Eq. (1) a more general criterion for strong contact formation was proposed in [39].

The author of [24] unequivocally connects compact strength with parameter τ/t_m obtained with different SW pressures. At the same time pressure itself may determine the strength of compacted specimens. The comment that the role of this parameter is unimportant since static pressure of the same value does not lead to bond formation [24] is not altogether valid. In fact, the role of dynamic pressure may differ from static pressure, e.g., by the different nature of oxide film breakdown, the degree of contact region plastic deformation, etc. Therefore, it would be interesting to study the behavior of compact strength in relation to particle size governed by the ratio τ/t_m with the same pressure.

The criterion advanced in [40] differs in principle from that in [24] and it is qualitatively similar to that in [22]

$$L = \frac{\varepsilon_0}{c(T_s - T_0) + \lambda} > L_{\min},$$

where c is average value of heat capacity between T_s and T_0 ; λ is latent heat of melting. It is clear that this criterion may be rewritten in the form $\varepsilon_0 > \varepsilon_{\min}$ [22].

It was shown in [40] that tensile strength, greater than half this value for monolithic material, is achieved with $L_{\min} \approx 0.22$ for alloy AISI 9310 powder with a particle size of 60 μm and an initial porosity of 1.7. This corresponds to $\varepsilon_0 = 3.2 \times 10^5$ J/kg. Another important condition for forming a strong compact in [40] is assumed to be greater time for the specimen before arrival of the low-pressure wave t_r compared with the time for melt crystallization along particle boundaries t_s :

$$t_r > t_s.$$

A similar requirement was advanced previously in [16]. These conditions ($L > L_{\min}$, $t_r > t_s$) limit the region for compaction to a plane of normalized parameters $t_r - \varepsilon$.

A model was built in [41] for forming molten zones along the periphery of powder particles assuming that generation of thermal energy occurs as a result of friction. The presence of melts leads to removal of oxide films from the surface of particles, and filling of pores and cracks in the compacted material [41].

Basic Properties of Materials Obtained by Dynamic Compaction. In spite of considerable potential for the compaction method considered for materials with a metastable structure noted in [5, 23-25, 34, 36, 39, 42, 43], it has so far found limited application. One of the reasons for this position is insufficient information about the properties of the materials obtained. Recently studies have appeared making up for this deficiency.

In [5] with explosive compaction of amorphous powders monolithic rods have been prepared with diameter 8 mm and length 105 mm of alloy $\text{Pd}_{77.5}\text{Cu}_6\text{Si}_{16.5}$. Results of x-ray analysis, measurement of hardness, sound velocity, elasticity moduli, and also use of the differential scanning calorimetry method, have confirmed retention of the original amorphous structure in monolithic specimens [44]. The properties of compacts indicate that not only is it possible to obtain a bulk specimen of amorphous material, but to achieve in this way mechanical properties equivalent to the original for the foil, powder, flakes, etc. [44]. For monolithic specimens of alloys $\text{Fe}_{30}\text{Ni}_{40}\text{P}_{14}\text{B}_6$, $\text{Ni}_{37}\text{Mo}_{23.5}\text{Fe}_9\text{B}_{10.5}$ a density of 97.6 and 97.3% has been obtained, and a microhardness coinciding with the original value [44].

In experiments for compacting alloy $\text{Fe}_{40}\text{Ni}_{40}\text{P}_{14}\text{B}_6$ [45], which was carried out using a gas gun, specimens were prepared 25 mm in diameter and 10 mm thick having a density of 7.49 g/cm³, which was 99.8% of the theoretical. X-ray analysis showed that the specimen remains amorphous whilst the calculated temperature does not exceed 600°C, whereas $T_c = 412^\circ\text{C}$. Plotted T-T-T diagrams for this alloy showed that retention of the amorphous state for specimens of this size is only possible with cooling of it from a temperature of 500°C [46].

This contradiction is probably connected with the calculation method in [45] for residual temperature. In tests it is the result, as a minimum, of two-stage compression which leads to

less heating with the same final density than single-stage shock-wave processes receiving attention in [45]. Consideration of this situation makes it possible to explain this contradiction.

A study of surface breakdown in [45] revealed that in testing materials corresponding to a calculated temperature $T_c = 600^\circ\text{C}$, fracture morphology is typical for lamellar metallic glasses. At the same time it is noted that even in cases when it is possible to avoid crystallization, there is a low value for ductility. The method of dynamic compaction may find best use for more ductile amorphous alloys [45].

It is necessary to note a feature of tests on dynamic compaction of amorphous materials without evacuation. Air in the specimen fills pores and is then distributed throughout the volume of the material. It is easy to determine that the average gas content by weight has a value of $\sim 10^{-2}\%$. However, if gas molecules are concentrated in the molten region along boundaries, then with a low value of them (e.g., $\sim 1\%$) the content of gases in the molten zone will also be $\sim 1\%$. This content of oxygen atoms leads to a marked reduction in amorphous alloy ductility for transition metals, e.g., the system Zr-Cu [47].

A detailed study of the properties of Metglas 2826 alloy was carried out in [48]. It is noted that retention in specimens of an amorphous structure is not in itself sufficient to obtain physical characteristics comparable with those for strip. A compact made of strip differs by the presence of boundaries between particles whose properties may to a significant degree determine material characteristics. Therefore, it is important to have development for the compacts of high wear resistance comparable in the region of low and medium rates with the strengthening characteristics (~ 900 HV) for a tool steel [48]. The comparatively low corrosion resistance obtained for compacts is connected in [48] not only with partial ordering of the alloy, caused by residual warm-up, but also with its structural defects. This is related in particular to porous zones of the melt and zones of intense sliding inherent in the dynamic compaction process. The ultimate tensile strength of specimens in [48] was a value equal to half that for the amorphous strip, which is explained by the presence of microcracks in regions of insufficiently stable bonds between planes of powder particles. The hardness of compacted material with $T_p = 600^\circ\text{C}$ increases by about a factor of 1.5 compared with the original hardness, and then it decreases. This behavior is due to ordering processes and crystallization occurring in glasses and under normal heating conditions.

Compaction of $\text{Fe}_{40}\text{Ni}_{10}\text{P}_{16}\text{B}_4$ and $\text{Fe}_{38}\text{Ni}_{38}\text{B}_4$ alloy powders and fibers was carried in [49]. The plates obtained were $200 \times 50 \times 3$ mm in size with a density of 90 to 95% of the theoretical. As in [48], an increase in microhardness was observed starting from a value $\text{HV}_{50} = 6400$ MPa to $\text{HV}_{50} = 8000-8500$ MPa. On the basis of studying the thermal stability of material after explosive compaction the authors of [49] note an increase in crystallization temperature which depending on loading parameters reached 100°C . Formation of vacancies in amorphous materials as a result of shock-wave processes in particles noted in [49] hardly leads to additional increase in T_c . This is indirectly confirmed by the independence of microhardness for amorphous foils after shock-wave loading with a pressure up to 40 GPa [50]. However, it should be noted that some increase in T_c is possible in principle as a result of the fact that a considerable part of the material (up to half of the volume) may be cooled from the melting temperature to an equilibrium state at a rate greater than in preparing the original powder or strip [28].

The authors of [51, 52] in shock-wave compacting powder of amorphous alloy $\text{Fe}_{40}\text{Ni}_{10}\text{P}_{14}\text{B}_6$ obtained a density of 83-96% of the theoretical. Joining of particles was observed both through a molten layer 1-5 μm thick, and without it. In contrast to the results in [49] the crystallization temperature up to loading rates of 700 m/sec varied insignificantly compared with the initial value, the same as for heat of transformation. The coercive force measured in the work was $H_c = 3-4$ A/m, and the saturation flux density $B_s = 0.58-0.64$ T.

The authors of [53-55] confirm compacting alloy $\text{Fe}_{75}\text{B}_{15}\text{Si}_5$ (Metglas 2605-S2) to 92-99% of the limiting density. In this way values of $H_c = 100$ A/m and $B_s = 1.2$ T were achieved. These results point to a high level of magnetic characteristics for compacts prepared by the dynamic method, which is a promising application.

Alloy powders $\text{Fe}_{70}\text{Ni}_{10}\text{P}_{14}\text{B}_6$ and $\text{Fe}_{70}\text{Cr}_{10}\text{P}_{10}\text{C}_7$ have been compacted by explosion [56] both by the standard scheme, and using a selection of plates of different density placed between

the explosive and the powder (DIS scheme); which leads to multistage SC close to isoentropic. It is noted that after shock-wave compression the initial random distribution of flaky amorphous particles is retained, whereas with compression by the DIS scheme there is lay-up of them parallel to the compressive wave front. A change in initial temperature to -196°C did not affect the value of final density (96-99% with $p = 5\text{-}20$ GPa). For alloy $\text{Fe}_{40}\text{Ni}_{40}\text{P}_{10}\text{B}_0$, compacted by the DIS scheme the initial maximum of the crystallization peak decreases on average by 4°C compared with the original condition, which is explained in [56] by formation of crystalline phase nuclei. A detailed analysis of the structure of compacts using x-ray diffraction and γ -resonance spectroscopy was carried out. Use of the DIS scheme promotes retention of the amorphous phase.

Compacting by explosion of amorphous alloy $\text{Ni}_{89}\text{P}_{11}$ powder was carried out in [57] at pressures of 3.7, 4.4, and 5.1 GPa. With the middle pressure value a monolithic amorphous sample was obtained, but with $p = 5.1$ GPa areas of local crystallization with a dendritic structure developed.

Powder of amorphous alloy Markomet 1064 ($\text{Ni}_{52.5}\text{Mo}_{38}\text{Cr}_8\text{B}_{1.5}$, particle size $50\ \mu\text{m}$) was compacted in [58] with SW lasting $2\ \mu\text{sec}$ at $p = 4\text{-}12$ GPa. Before shock compression powders were evacuated, and the initial porosity was close to two. In the specimens obtained with an increase in shock-wave pressure there was a fall in microhardness connected with a change-over from the amorphous phase to a microcrystalline condition. With an increase in specific shock compressive energy to $1.22\epsilon_m$ (where ϵ_m is the amount of heat necessary to warm up a unit mass to the melting temperature) a microcrystalline structure with a considerable number of macropores was detected.

In [59] on the basis of a procedure developed in [60] there is a study of local magnetic anisotropy characteristics in ferromagnetic material $\text{Co}_{58}\text{Ni}_{10}\text{Fe}_5\text{B}_{10}\text{Si}_{11}$ compacted by explosion. The size of the local anisotropy field H_a and the size of the region for relative ordering of the anisotropy orientation axis $2r_e$ (where r_e is correlation radius) record changes in the structure of amorphous alloys during grinding and compacting even in the case when by means of diffraction and calorimetric measurements such changes are not observed. An ordering effect for powder particles was recording in [59] consisting of the fact that they line up parallel to the shock wave front, as in [55, 56].

An important comment is made in [59]; in spite of the short duration of the explosive compaction process, due to the dependence of diffusion coefficient on temperature and possibilities for creating melts along particle boundaries, the typical scale of diffusion processes may be significantly greater than in static compaction methods [4, 61-63]. Thus, in dynamic compaction processes it might be expected that stronger bonds between particles would be obtained than in static methods. The magnetic properties of compacts prepared under static conditions are close to those for dynamic methods, although the latter procedure exhibit a number of advantages [54, 61].

An important application of shock-wave compaction is preparation of bulk specimens of fine microcrystalline rapidly quenched alloy powders. The material obtained by dynamic compaction differs from that consisting of strengthened particles, connected with rapidly quenched melt along their boundaries [64]. This leads to high microhardness [19, 24, 64, 66], greater than with other strengthening methods, including the action of SW on monolithic materials of the same composition [17].

In [24] it is assumed that an improvement in bond quality between particles may lead to a strength lying on the extrapolated dependence between this parameter and hardness obtained for monolithic material. This claim is supported by the results for aluminum. On the basis of the proposed extrapolation the strength value expected for St. 304 is 1200 MPa. In this connection it is noted that a hardness of 350 HV for monolithic stainless St. 304 may be obtained with an SW pressure of 40 GPa. A further increase in p does not increase hardness [67]. The strength is 797 MPa, which exceeds the original strength by a little, and it is much less than the expected (1200 MPa) strength based on hardness data [24]. Thus, the extrapolation proposed is not apparently always valid.

The mechanism of the increase in hardness for powder particles during compaction is not clear. In [65, 68] it is connected with passage of a plane wave through the internal region of particles. In this case for tests, e.g., in [17], it would assume existence of a pressure of ~ 40 GPa within particles of St. 304, whereas that found from the law of conservation $p = 1.2$ GPa, i.e., more than an order of magnitude less. Furthermore, for the SW considered their propagation velocity is several times less than the sound velocity of particles, i.e.,

an SW does not form in a particle and its volumetric compression has a rather isentropic character. Therefore, drawing upon the shock-wave mechanism in order to explain the increase in hardness of powders can hardly be considered valid.

In some cases a contribution to the high hardness of compacts may be made by rapidly quenched areas along particle boundaries [18]. It is evident that this phenomenon is connected with the high rate of plastic shape change for particles leading to effects similar to shock-wave strengthening of monolithic materials. In this case, the correlation between these methods should be in the degree and rate of plastic deformation, and not in the SW pressure amplitude.

The greatest strength value (1.3 ± 0.14 GPa) has recently been achieved for compacts of steel AISI 9310 powder [40, 66]. High-strength properties have been obtained for materials consisting of mixtures of two or three substances, such as aluminum, steel, lead, which are difficult or impossible to obtain by other methods [69, 70]. The tensile strength of Mo specimens (0.76 GPa) is comparable with its value for rolled sheet [58].

A good illustration of the potential for the method of shock-wave compaction followed by heat treatment (from the point of view of creating strong specimens) is its use for preparing a matrix with a yield strength of 1.5-2 GPa for the shock-wave compaction process itself [70, 71].

Strength values comparable with material parameters obtained by gas-static compaction and extrusion have been achieved for titanium alloy Ti - 6Al - 2Sn - 4Zr - 2Mo in tests on explosive compaction with prior heating of powders [72].

A characteristic difference, generally speaking not typical for shock-wave compaction, is the comparatively high (12.5%) ductility value obtained in [72]. As emphasized in [39], the maximum material ductility obtained in tests without prior heating is 8% for aluminum with a hardness of 84 HV, which markedly exceeds this property for material (respectively 3% and 45 HV) obtained by traditional technology.

Only in individual works is there information about such a compact parameter as fracture toughness, which according to measurements in [17] for St. 304 was comparable with that for normal stainless steel (31 and 32 MPa·m^{1/2}, respectively).

The unique structure of materials obtained by the shock-wave method may lead to higher fatigue characteristics [39]. It is noted in particular that compacts of aluminum have a fatigue strength with 10^7 cycles greater by a factor of two than for normal material.

High resistance to abrasive wear has been obtained for compacted steel + aluminum powder mixtures, and also with addition to this mixture of lead particles [36, 39].

The characteristics noted for compacts of rapidly quenched powders make it possible to use them effectively in the following applications [70, 71]: creation of quite strong low-density blanks with a high degree of property homogeneity suitable for further extrusion, and preparation of blanks made of granular nickel and aluminum alloys. Atomizer nozzles of complex geometry made of tool steel have been created by means of dynamic compaction technology [73], since normal powder metallurgy methods lead to shrinkage and a change in dimensions. The potential is also noted in [73] for compaction of titanium alloys and creation of blanks not yielding to cold compaction with sufficient strength under further hot forming.

Action of Shock Waves on Monolithic Amorphous Alloys

A study was first made of the effect of SW on monolithic amorphous alloy characteristics in [50]. In it, tapes and wires of alloys $\text{Fe}_{80}\text{B}_{20}$ and $\text{Fe}_{38}\text{Ni}_{10}\text{Mo}_4\text{B}_{18}$ were loaded with SW having a pressure of 15, 25, and 35 GPa, and a pulse duration of 2×10^{-6} sec. Hardness measurement and a study of specimens by means of electron and ion microscopes did not reveal any marked changes in the structure of materials after loading up to $p = 35$ GPa. It is assumed that [50] amorphous material characteristics may only change with $p \geq 90$ GPa, when crystallization effects due to the closeness of the crystallization temperature to the residual temperature might be expected.

However, consideration of the results of shock-wave action on amorphous alloys only from the point of view of heating is not entirely correct. In fact, the properties of amorphous materials are mainly due to the presence of a free volume with a value $\sim 1\%$ [74]. On the other hand, the increase in density under SC with $p = 10$ -50 GPa is 5-35% for metals [75], i.e., the change in volume for an amorphous alloy under shock compression may exceed by

an order of magnitude the free volume of the amorphous alloy. It is clear that if an irreversible increase (reduction) of it is only possible as a result of close ordering, without transport of it to a free surface, e.g., by the "breakdown" scheme [76], then SC or tension in the low-pressure wave may affect the magnitude of the free volume. Consequences of this process may be most clearly revealed in the crystallization characteristics of materials as the most sensitive to structural features.

The authors of [77, 78] assume that the amorphous state is an ideal original material for synthesizing recrystallized phases at high pressures and temperatures, since it is a uniform mixture of substances at the atomic level having a high free energy. In particular, under pressure crystallization is possible into a single-phase structure [78, 79]. The particular role of dynamic pressure is expansion of the spectrum of phases obtainable. For example, achievement at the highest temperature of a superconducting transition is connected with formation under pressure of a new unidentified phase with a greater Nb content than in alloy Nb₃Si [78].

Magnetic structural analysis was used in [80] in the same way as in [59] to study the structure of amorphous ferromagnetic alloys Co₅₈Ni₁₀Fe₅B₁₀Si₁₁ and Fe₀₇Ni₆B₁₀Si₁₁ in the shock compression region 10-35 GPa. For example, it was revealed that the behavior of these alloys has a different character. Whereas for the first alloy there is a uniform decrease in correlation radius from the original $r_e = 220$ to 90 Å with $p = 35$ GPa, for the second there is an increase in this parameter from 150 to 900 Å with the same pressure. This difference in alloy behavior is not explained by the authors of [80].

Preparation of Rapidly Quenched Materials Using Shock-Wave Compression

The features of material deformation in shock waves, connected with nonuniform distribution of thermal energy throughout the volume promote creation of rapidly quenched materials, including amorphous structures. The first time an amorphous material condition was obtained by shock-wave compression, it was recorded in quartz [6, 7]. In particular, in the region where the average material temperature is less than the melting temperature, formation of diaplectic glasses was observed as a result of material melting in zone of adiabatic shear their solidification up to the instant of a complete pressure drop [7]. Similar formations for metal alloys have not yet been detected.

Shock compression has a greater potential as a result of strong nonuniform heat generation (see Figs. 1 and 3) for porous materials. A microcrystalline phase was detected in [17, 65, 81] with a typical structure size of less than $1 \mu\text{m}$ along the boundaries of St. 304L particles, nickel alloy MAR M-200, and alloy Al-11% Si. In the case of St. 304L these regions were quite lamellar and they were connected by particles with high hardness. An amorphous phase along boundaries of AlN particles was found in [82] by means of transmission electron microscopy. Its development was due to enrichment of surface layers with silicon recorded by microanalysis of the composition.

A description and analysis of microcrystalline structures formed by rapid quenching of surface layers in granular alloys based on iron, nickel, and aluminum is given in [18, 19]. The importance of using this method for preparing rapidly quenched alloys consists of the fact that it provides quenching under high pressure. This makes it possible to expect new properties for the materials obtained compared with normal quenching methods.

Interesting observations of a significant amount of amorphous phase developing during SC, initially microcrystalline, with a small addition of amorphous phase for alloy Markomet 3.11 are given in [58]. The method suggested in [8] has a special potential for preparing rapidly quenched states for a certain class of materials. It is based on melting a substance with anomalous path for the melting curve under pressure close to the the minimum T_S , and subsequent melt quenching as a result of a drop in pressure.

CONCLUSIONS

The features of dynamic loading for porous materials make shock-wave methods promising, both from the point of view of compacting rapidly quenched alloys, and from the point of view of carrying out the quenching process itself. Shock-wave compression methods may be useful for expanding the spectrum of crystalline phases formed during crystallization of amorphous alloys.

The authors thank V. M. Titov and A. A. Deribas for stimulating preparation of this communication, R. Prummer, D. Raybould, M. Wilkins, K. Cline, and R. Graham for discussing the problems touched upon in the work, and A. V. Molotkov, A. N. Lazaridi, and K. I. Savinkov for help in preparing and carrying out experiments.

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