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Shock compaction of AlMgSi0.5 spheres

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Shock compaction of AlMgSi0.5 was realized by using a LEXAN projectile with a velocity of 1655 m s^{-1}. The dynamic pressure in the zone of impact was 8 GPa in the sample in the target at room temperature. The sample consisted of spheres of two particle size fractions (100–200 μm and 200–315 μm) separated in layers through which the same shock wave was passing. The appearance of non-porous interparticle contacts in the impact zone, with the content of melted areas up to 10% was detected in the case of the larger particle fraction only. Smaller particles had no tendency to form the strong interparticle contacts, not even in the first layers in the direction of the shock wave. TEM analysis showed the presence of an intensively deformed structure in the zone of the planar shock wave, as well as the structures with very poor signs of recovery and recrystallization in particle contact areas. The hardening effect of the shock wave was obvious, so that microhardness in the zone of the planar wave in larger particles had reached the value of 120 Hv, much higher than the microhardness of the initial powder (70 Hv).

1. Introduction

Shock compaction is the method of consolidation of powders which eliminates the appearance of thermally activated microstructural changes characteristic in conventional thermomechanical processing. Hence, it is very convenient for the processing of non-equilibrium powders with specific uniform microstructures [1, 2]. Two methods have been used to obtain the shock state required for the powder: explosive detonation [3] and impact of high velocity projectile [4]. In this study the high velocity projectile impact was used for the shock compaction, because shock parameters could easily be controlled [5, 6]. In this paper the shock compaction of AlMgSi0.5 is reported, this has not been investigated before although it is very interesting from the standpoint of the possibility of studying the strengthening phenomena under the influence of shock waves. This alloy is in the group of materials which harden by precipitation of disperse intermetallic phases. By using a shock wave in the cold compaction it was possible to eliminate the decrease of strength which occurs during longer thermomechanical treatment over 200 °C, owing to the coagulation of dispersed phases. The use of spheres made studying the phenomena at the contacts or in the bulk of the particles during the shock compaction easier.

2. Experimental procedure

The alloy of the nominal composition (Al 91.75%, Cu 4.8%, Mg 1.5%, Mn 0.6%, Si 0.5%, Fe 0.4%, Cr 0.10% and Zn 0.25% was cast in the Aluminium Combine, Podgorica, where it is one of the production programme of alloys for plastic fabrication. Electrodes for the rotating electrode process, in this laboratory, were made of cast ingots [7]. The diameter of the consumer electrode was 0.017 m, the angular velocity 942 rad s^{-1} and the current 54 A. The atomization was done in helium with a small content of argon. The powders so obtained had a regular spherical shape. In the case of smaller particles, a dendritic structure was dominant. In the case of larger particles a "cellular" structure was characteristic. In Fig. 1 a typical morphology of AlMgSi0.5 powders obtained by the rotating electrode process is shown.

The compaction of AlMgSi0.5 spheres was done by means of the quasiplanar shock wave obtained by the impact of the high velocity projectile that has been launched by the electrodynamic macroparticle accelerator [5]. The cross-section of the projectile made of LEXAN was 12 × 12 mm. Its velocity was measured precisely (in the range of 1% error). The data, including specific mass and shock-Hugoniots for materials of projectile and target, and the measured velocity, were used for the calculation of the dynamic pressure in the boundary layer of the sample in the target [5]. The schematic view of a cross-section of the target with the capsulated sample and the direction of the wave propagation after the planar impact is shown in Fig. 2.

The propagation of the shock wave was complex in deeper layers of the porous material and thin sample was used for this study. The sample consisted of the powder poured in five layers, whose total thickness was not more than 1.5 mm, with a diameter of 40 mm (Fig. 3). There was a great difference between shock impedances of the target material and the sample material. In order to minimize the effect of the reflected shock wave the target was made of various

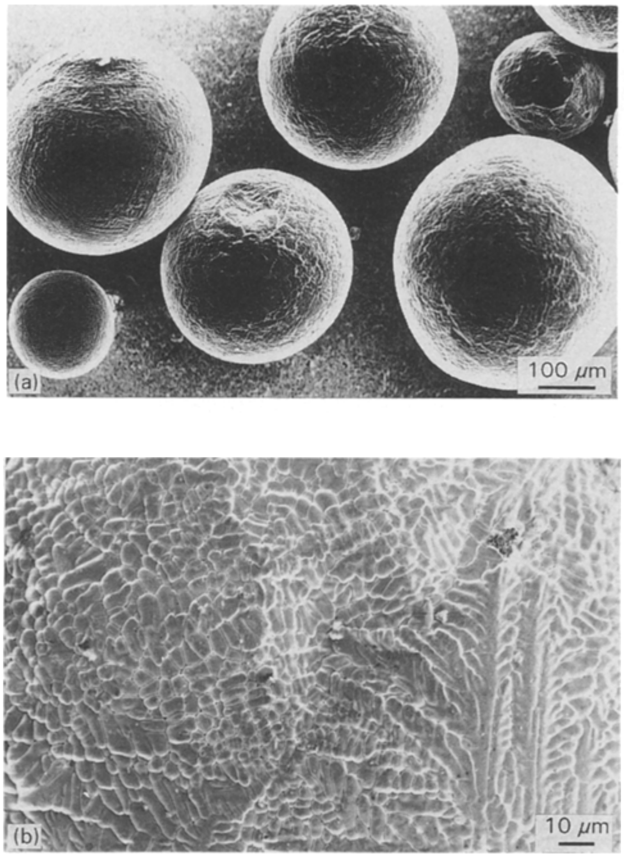

Figure 1 SEMs of AlMgSi0.5 spheres obtained by the centrifugal atomization, i.e. by the rotating electrode process.

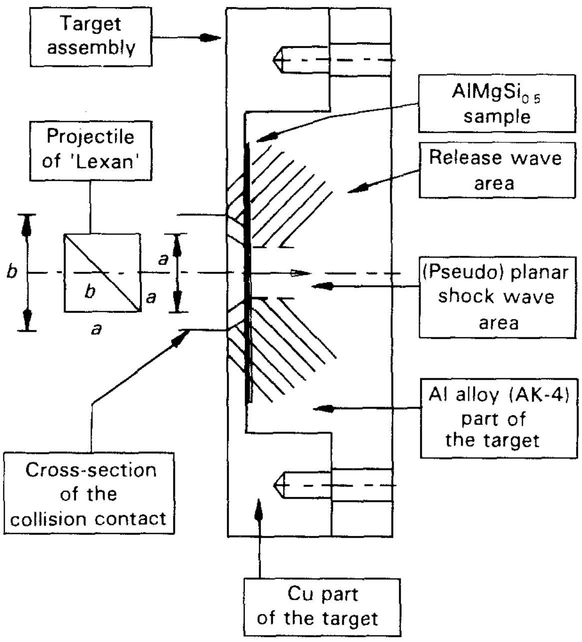

Figure 2 Schematic view of the target in interaction with the projectile and the direction of the shock wave propagation.

materials. The front side, which came into direct contact with the projectile was made of copper (known Hugoniot). The back side was made of the Al-alloy AK-4 with the following content of alloying elements: Cu, 1.8–2.5%; Mg, 1.4–1.8%; Fe, 1.3–1.8 % Ni, 1.3–1.8%; Si, 0.5–1.2%. The shock impedance value of the target's back side material had to be as

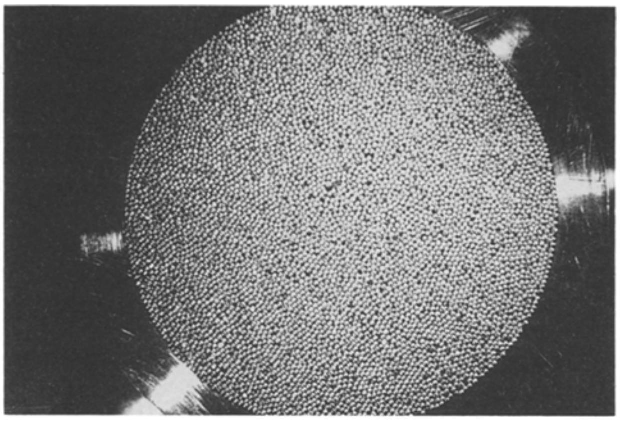

Figure 3 AlMgSi0.5 spheres in the sample support before shock compaction.

TABLE I The characteristics of AlMgSi0.5 powder and parameters of compaction

Layer	Particle size (μm)	Specific pressure of pre-compac. (GPa)	Projectile velocity (ms^{-1})	Shock pressure (GPa)
1	100–200			
2	100–200			
3	200–315	0.44	1655	8
4	200–315			
5	200–315			

close as possible to the shock impedance value of the powder sample. The appearance of the reflected shock wave resulted in the breaking of interparticle contacts already formed.

The particle size across the layers changed from 100 to 200 μm in first layers and from 200 to 315 μm in the last layer, looking from the impact surface. The initial packing density before the shock compaction was very important. Strong contacts and the consolidation during shock compaction were registered only in the case of samples where the particles were in intimate contact. For this reason the powder was prepressured at the ambient temperature. The applied pressure did hot cause the formation of strong contacts, but resulted in the close contact of spheres. The particle sizes, the parameters of pre-compaction and the parameters of the shock compaction for the studied samples are given in Table I. In the target the sample was completely encapsulated by cold prepressing.

From numerous experiments under similar conditions, only those experiments where impact was planar were taken into account for the analysis. It is the basic condition for the exact calculation of dynamic pressure at the boundary between the sample and the copper part of the target. The criteria for the (pseudo) planar impact were the outlook, the symmetry and the dimensions of the crater obtained by the projectile impact on the target. A typical crater in the target caused by planar impact is shown in Fig. 4.

The microstructures were analysed by direct observation of surfaces using scanning electron microscopy (SEM) (JEOL-7) and transmission electron

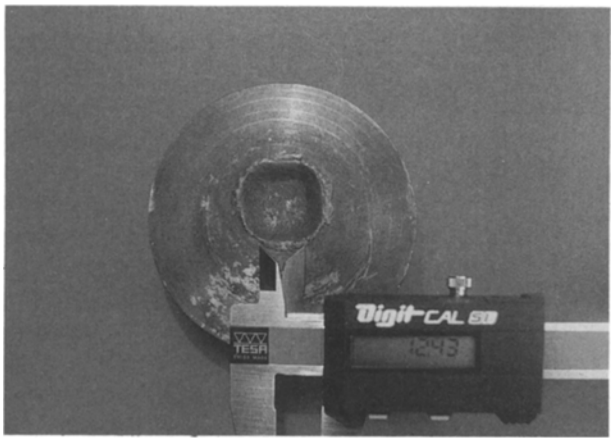

Figure 4 A typical crater made by the planar impact.

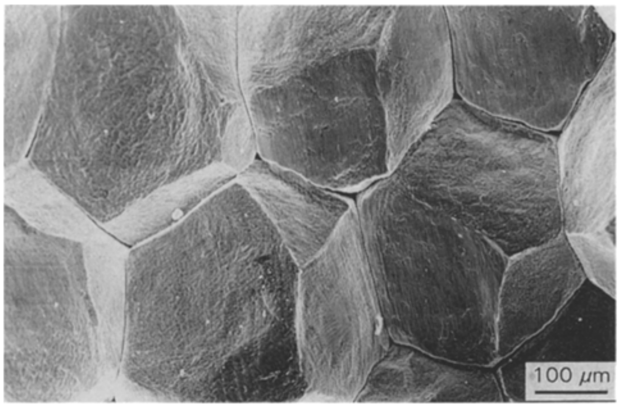

Figure 5 SEM micrographs of AlMgSi0.5 spheres in the third layer looking from the shock side.

microscopy (TEM) of foils (JEOL 2000 FX). The foils were prepared by electropolishing in a solution of 25% nitale cooled at $-14\,^{\circ}C$, and then washing in flowing ethanol.

The microhardness of the powder and the compacts were measured by the semi-automatic equipment PMT-3 with a diamond needle pyramid shaped with quadrate base and top angle of 136°. The effects of surface hardening of previous polishing were minimized by using the higher load (100 g). Larger particles had an average hardness of 71 Hv (kg mm^{-2}) and smaller particles 99 Hv. The higher value of the microhardness of smaller particles is in accordance with the fact that the increased degree of cooling improved microstructural refining by creation of very fine disperse phases (Mg_2Si before all) which resulted in the increase of hardness.

3. Results

Although a relatively high dynamic pressure was used for this class of alloys, the first layer of spheres at the impact surface (a particle size of 100–200 μm) did not show any sign of consolidation. The effects of compaction are not obvious earlier than in the third layer looking from the surface of impact. The last layer of particles were tightly connected with the layer of target made of Al AK-4 alloy and it was impossible to separate them.

Only the layers of larger particles (3–5) were sufficiently compacted to enable investigation by electron microscopy. The results of SEM of the third layer (particle size 200–315 μm), looking from the side impact, are shown in Fig. 5. It is obvious that the particles were deformed and as a results of shock compaction they obtained a polyhedral form, but without strong bonds which would cause a high strength of compacts [8, 9]. However, the last layer of spheres in the sample formed strong bonds with the support and a difference between the two zones (planar wave and release wave) was easily observed, as is shown schematically in Fig. 2.

The results of the (quasi) planar shock wave in the last layer (looking from the impact side) are shown in Fig. 6. The analysis showed a completely non-porous

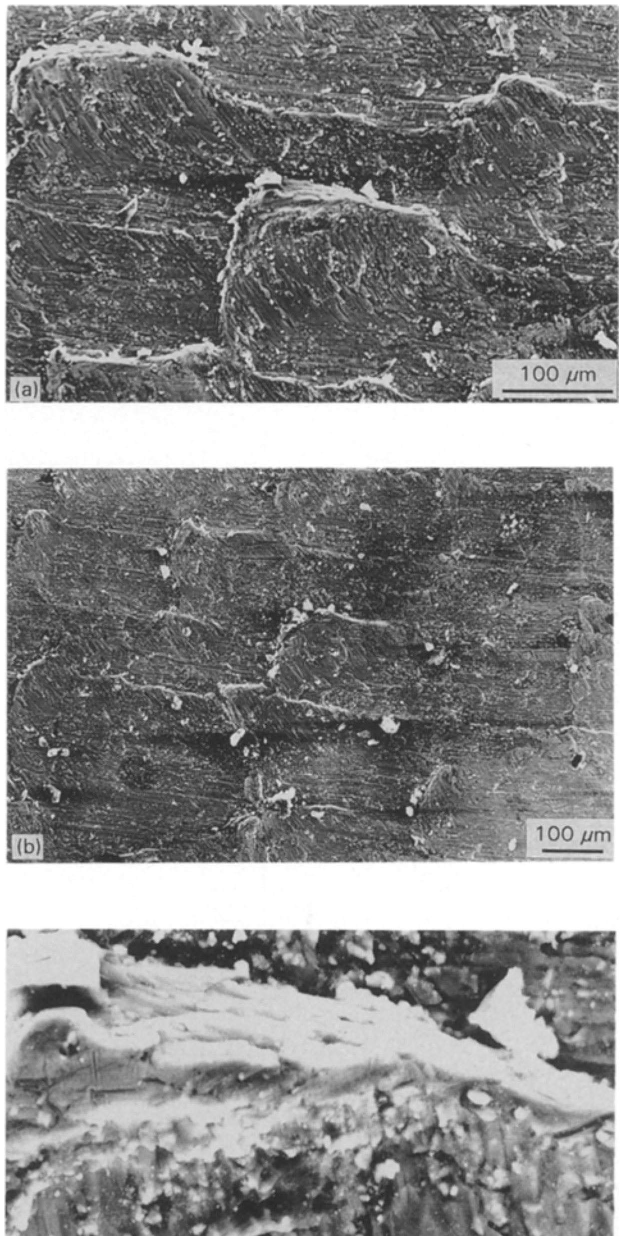

Figure 6 SEM micrographs of the zone of planar impact in the last layer of particles 200–315 μm (a) and (b) the impact zone; (c) magnified detail of the melted area.

Figure 7 TEM analysis of shock compacted AlMgSi0.5. (a) the interparticle contact area; (b) the matrix structure of spheres; (c) the substructure of the interparticle contact area.

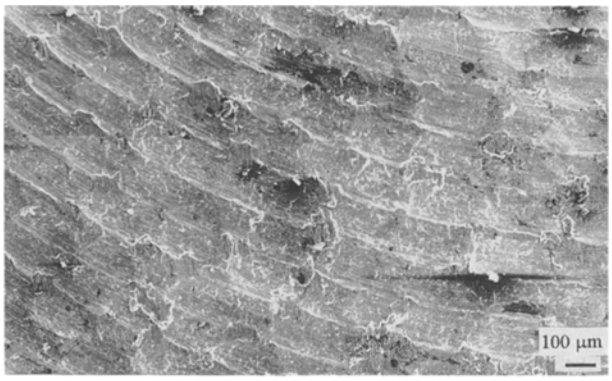

Figure 8 SEM micrograph of the release wave zone layer of particles (200–315 μm).

surface with no cracks and the appearance of melted places (lighter parts on the micrographs), whose partition in this zone was up to 10%. The energetic dispersion X-ray analysis (EDS) of the melted zone did not show any qualitative changes compared to the bulk of particles. TEM analysis (Fig. 7) showed the presence of an intensively deformed structure in the zone of the planar waves as well as the structure with very poor particle contacts. The confirmation about the high deformation of matrix grains was obtained from the presence of the sub-grains and very dense dislocation loops in the matrix. The structure of interparticle contact showed signs of disappearing at boundaries between particles as a consequence of melting, and other signs of the recovery and particle recrystallization, especially pronounced in the zone of the planar wave. The bulk dislocations in this zone are present in the shape of dislocation sub-structures with the appearance of clearly seen boundaries. The zone of the release wave showed a deformed structure with no evidence of melted points.

The dynamic pressure rapidly decreased in the zone of release waves, in the last layer the material flowed in the direction of wave propagation (Fig. 8). The study of the zone influenced by the release wave was only possible in the last layer, just near the back side of the target made of Al-4 alloy. The SEM analysis of this zone is shown in Fig. 8.

The microhardness in the zone of the planar wave on the last layer of the sample was measured across

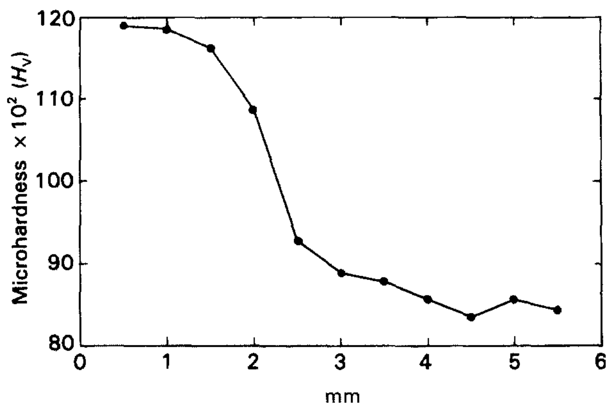

Figure 9 The changes of microhardness from the centre to the edge of the zone of the (quasi) planar wave.

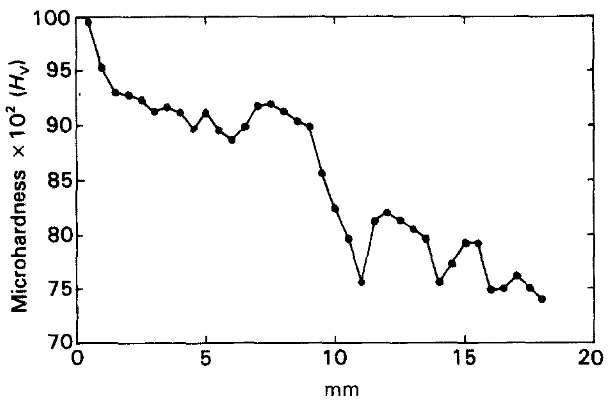

Figure 10 The change of microhardness in the zone of the release wave from the boundary of the (quasi) planar shock wave to the edge of the release wave zone.

the diameter of the zone from the centre to the edge, the result is shown in Fig. 9. The variation in hardness in the zone of the release wave measured from the boundary with the zone of the planar wave upto the edge of the zone of the release wave, is shown in Fig. 10. The microhardness of compacted material in the centre of the impact zone increased to the value of 120 Hv compared to the initial 70 Hv of the powder. The microhardness slowly decreased with an increase in distance from the centre of the zone of the planar wave, to the boundary edge with the zone of the release wave. Larger oscillations of the values of microhardness of edge parts of the zone of the planar wave could be the consequence of the specific shape of this zone (crater shaped). At the edge of the zone of the release waves the microhardness of the initial powder. It was not possible to determine the pressure precisely, nor the relationship of deformation strengthening versus pressure in the zone of the release wave, but it is certain that the pressure was significantly lower than in the zone of the planar wave.

4. Discussion

The elimination of the wave reflected from the back side of the target enabled a clear explanation of the obtained experimental results [5]. The effect of the propagation of approximately the same shock wave through the small thickness of the sample with the layers of various particle sizes (identically prepared) of the same powder were quite different. In the case of smaller particles (100–200 μm) strong interparticle contacts were not formed, but in the case of larger particles (200–315 μm) non-porous interparticle contacts with a significant content of newly formed liquid phase (the portion of melted points is up to 10%) was observed. The microstructure of AlMgSi0.5 spheres compacted by the shock wave were characterized by two regions:

1. an interparticle region intensively plastically deformed with the appearance of melting and recrystallization;
2. the bulk of spheres, which remained practically unchanged with the exception of characteristic changes of hardening.

The optimal consolidation was realized by plastic deformation of particles causing the formation of strong interparticle contacts. At high velocity of deformation, i.e. typical for shock compaction, the rise in temperature was localized at the surface layers of particles [10, 11]. The bulk of particles were not softened by the rise in local temperature, and did not participate directly in contact formation, but were characterized by an intensive deformation strengthening. The quantity of material which was melted during the propagation of the wave front depended on the particle size, the applied pressure and time of shock duration. The obtained results confirm that an increase in temperature on the surface of contacts, and the energy stored in them, rise with an increase in particle size resulting in a large content of liquid phase, strong contacts and a non-porous structure.

The study has shown the hardening effect of the shock wave in the case of AlMgSi0.5 spheres. Microhardness in the zone of the planar wave reached the value of 120 Hv, which is much higher than that of the value of the powder (70 Hv) and casted alloy (50–70 Hv). The hardness decreased towards the edge of the zone of the planar shock. The zone of the release wave showed small variations in microhardness. In the zone of the release wave the dynamic pressure progressively decreased with distance, so that hardening started at very low values of dynamic pressure.

5. Conclusions

Shock compaction of two granulations of AlMgSi0.5 spheres (100–200 μm and 200–315 μm), separated in two layers, by a shock wave of dynamic pressure 8 GPa was studied at room temperature. Non-porous contacts with a content of melted places up to 10% were found only in the case of larger particles in the zone of the planar wave. It was shown by TEM analysis that a very deformed structure appeared in the zone of the planar wave, as well as structures showing small signs of recovery and recrystallization in particle contacts. It was found that the shock wave had a hardening effect, so that the microhardness in the zone of the planar shock reached the value of ca. 120 Hv in the case of larger particles. It was much higher than the microhardness of the initial powder (70 Hv) and of the particles in the zone of the release wave.

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