

Accelerated Transport of Substances During Severe Plastic Deformation

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Abstract

The Severe Plastic Deformation (SPD) of the powder mixture is studied using the High Pressure Torsion method. Using the example of a mixture of aluminum, titanium and carbon powders, it is shown that SPD leads to accelerated mass transfer, which is expressed in an increase in the effective diffusion coefficient by more than 6 orders of magnitude. A hypothesis regarding the physical causes of this effect is put forward and substantiated.

KEY WORDS: *powder composite, transport properties, accelerated mass-transfer, diffusion*

1. Introduction

When creating new materials, the initial substances are typically combined in a liquid state. Solid-phase synthesis, which involves the joint plastic deformation of various substances under high pressure, opens entirely new possibilities in this area. This method was proposed by Nobel laureate P. Bridgman. In his works [1, 2], Bridgman published the results of his initial experiments on the creation of alloys and polymers. He employed an original technique based on twisting thin disc-shaped samples between two anvils. A force was applied along the axis such that the sample was compressed under a pressure of tens of thousands of atmospheres. This technique was subsequently named High Pressure Torsion (HPT) [3].

Since the late 1980s, HPT has been widely used to create ultrafine-grained (UFG) metals and alloys with remarkable physical and mechanical properties [3, 4]. In addition to HPT, other methods have been developed for the same purpose, which are collectively known as Severe Plastic Deformation (SPD) [5-7].

Research has shown that some SPD processes, such as Equal Channel Angular Pressing (ECAP) [8, 9], Twist Extrusion (TE) [10], Accumulative Roll Bonding [11], and others, like HPT, enable the alloying of metals and the synthesis of new materials. The results of studies on the application of SPD processes for such purposes are reflected in reviews [12-18].

A key stage in the synthesis of materials during SPD is the abnormally rapid delivery of atoms from various substances to specific locations within the deformed sample. This is achieved through solid-phase mixing processes occurring on different scales. Generally, the synthesis during SPD proceeds as follows: The initial substances enter the deformation zone in relatively large volumes, such as powder particles, wires, ribbons, plates, etc., with characteristic sizes ranging from tens to hundreds of micrometers. During SPD, these materials are thinned to micron and submicron sizes, separated into small parts, and intermixed. As a result, crystal lattice defects (vacancies, dislocations, grain boundaries, etc.) are formed, leading to the mechanochemical activation of substances and a sharp increase in diffusion coefficients. The high hydrostatic pressure in the deformation zone prevents material failure, creating conditions conducive to the formation of solid solutions, phases, and chemical compounds that are difficult or impossible to achieve with liquid-phase technologies.

Although the general picture of SPD synthesis is quite illustrative (as initially outlined by P. Bridgman in his early works [1, 2]), many details remain unclear. This hampers the full utilization of the immense potential of SPD synthesis, as achieving desired outcomes requires an understanding of the process's underlying patterns. The primary question arising in this context is: How exactly does SPD contribute to the accelerated mass transfer of various substances? This phenomenon is known as SPD-induced accelerated mass transfer [19, 20].

In this article, the effect of SPD-induced accelerated mass transfer is experimentally investigated using the example of HPT in a powder composite system Al-Ti-C.

2. Experimental Study of HPT Powder Composite in the Al-Ti-C System

2.1. Experimental Methodology

To obtain a powder composite in the Al-Ti-C system, a preliminary mixture was prepared using aluminum, titanium, and carbon powders. The powders were sieved to isolate the required fractions and then mixed in a gravitational mixer for 1 hour (component ratio: 45% wt. Al, 44% wt. Ti, 11% wt. C). The resulting mixture was then dried in a vacuum drying oven.

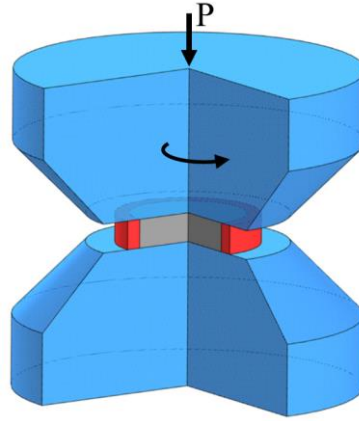


Fig. 1 Schematic of HPT

The HPT experiments (Fig. 1) were conducted at room temperature using a setup with flat anvils made of SHX15 steel. A restraining ring (the composite shell) made of annealed copper with a diameter of 10 mm and a height of 1.5 mm was placed on the lower anvil, and the previously prepared powder mixture was loaded into this ring. The upper anvil then compressed the composite with a pressure of $P=700$ MPa and was rotated around its axis by 180° . This cold deformation process resulted in metallized samples for further investigation.

X-ray phase analysis of the samples was performed using a "DRON-3" diffractometer. Their microstructure and local phase analysis were examined using a "VEGA3 TESCAN" electron microscope.

2.2. Experimental Results

Analysis of the electron microscopy results (Fig. 2a) revealed that during the deformation process, the powder composite was densified almost to a non-porous state. Along the particle boundaries, mutual solid-phase diffusion of aluminum and titanium into each other occurred, forming a transitional interlayer of titanium aluminide solid solution with varying component concentrations depending on the distance from the initial boundary between the particles. Micro X-ray spectral analysis (Fig. 2b) indicated that the mutual diffusion of the components extended up to $5 \mu\text{m}$.

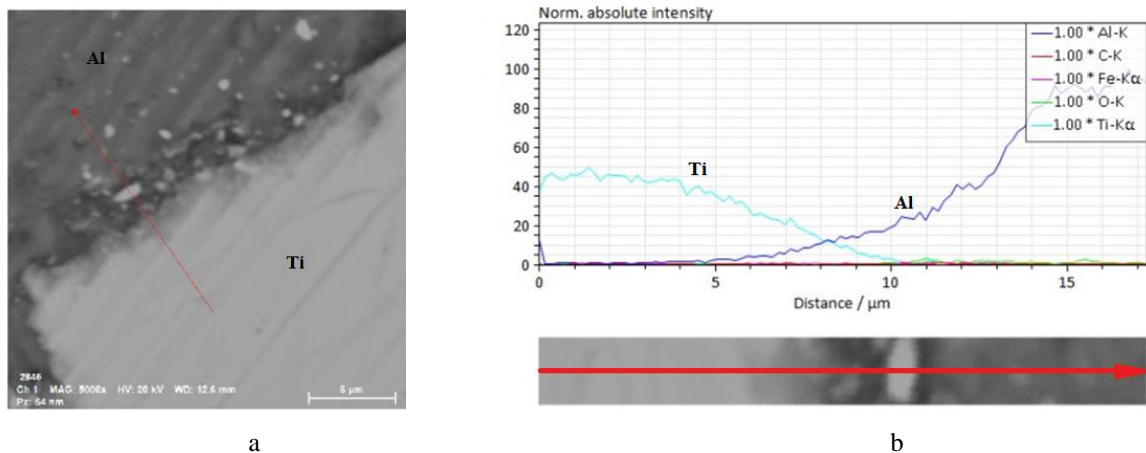


Fig. 2 Microstructure of the Al-Ti-C system composite: a – transitional layer between components; b – element distribution based on diffusion depth.

Microstructural and micro X-ray spectral analysis data are corroborated by X-ray phase analysis (Fig. 3). The X-ray diffraction pattern shows the presence of titanium aluminide compounds in the samples after HPT, indicated by three peaks corresponding to Al_3Ti . At the same time, the X-ray phase analysis demonstrates the absence of solid-phase

interaction between the composite's powder components and the copper shell, which is explained by their lack of solubility. During the deformation process, the copper shell is fragmented and dispersed into the composite volume. This transport effect can be utilized to alloy the system with copper or another material used as the composite shell.

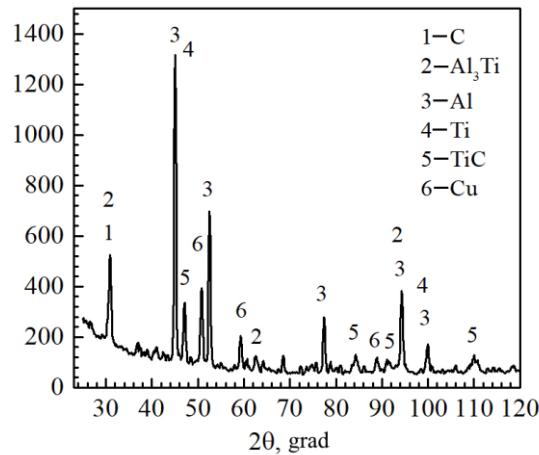


Fig. 3 Radiogram

3. Discussion

Let us assume that the mutual penetration of Al and Ti, shown in Fig. 2b, is due to diffusion. According to [21], the diffusion coefficient for aluminum in titanium at 400°C, a temperature not exceeded even by flashes at the particle contact boundaries during HPT, is on the order of 10^{-19} m²/sec. The duration of HPT in the experiment did not exceed 60 seconds. Under these conditions, the thickness of the diffusion zone, determined using the well-known formula, would be on the order of 10^{-9} m, which is three orders of magnitude less than what was observed in the experiment (see Fig. 2b).

Since the size of the diffusion zone is proportional to the square root of the diffusion coefficient, to match the experimental results, this coefficient must be six orders of magnitude larger than its value in the absence of particle deformation. This discrepancy highlights the effect of SPD-induced accelerated mass transfer. The question arises: What causes such accelerated transport of substances during Severe Plastic Deformation?

From our perspective, this effect can be explained within the framework of the Solid State "Turbulent" hypothesis. According to this hypothesis, HPT generates multiscale vortices due to the local blocking of simple shear [22]. These vortices lead to the transport and mixing of different substances, akin to how the different colored faces of a Rubik's cube are mixed. In this sense, this mechanism is analogous to turbulent diffusion in liquids, where the effective diffusion coefficient can exceed by many orders of magnitude the value in quiescent liquids [23].

4. Conclusions

This study demonstrates that Severe Plastic Deformation (SPD) significantly accelerates substance transport in solids. A hypothesis is proposed that this phenomenon is related to the generation of multiscale vortices during simple shear, which in turn is caused by its local blocking. In this sense, inanimate nature operates on the same principle as humans: when it's difficult to move, use wheels.

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