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Laser shock wave consolidation of nanodiamond powders on aluminum 319

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ABSTRACT

A novel coating approach, based on laser shock wave generation, was employed to induce compressive pressures up to 5 GPa and compact nanodiamond (ND) powders (4–8 nm) on aluminum 319 substrate. Raman scattering indicated that the coating consisted of amorphous carbon and nanocrystalline graphite with peaks at 1360 cm^{-1} and 1600 cm^{-1} respectively. Scanning electron microscopy revealed a wavy, non-uniform coating with an average thickness of 40 μm and absence of thermal effect on the surrounding material. The phase transition from nanodiamond to other phases of carbon is responsible for the increased coating thickness. Vicker's microhardness test showed hardness in excess of 1000 kg_f/mm^2 (10 GPa) while nanoindentation test indicated much lower hardness in the range of 20 MPa to 2 GPa. Optical surface profilometry traces displayed slightly uneven surfaces compared to the bare aluminum with an average surface roughness (R_a) in the range of 1.5–4 μm depending on the shock wave pressure and type of confining medium. Ball-on-disc tribometer tests showed that the coefficient of friction and wear rate were substantially lower than the smoother, bare aluminum sample. Laser shock wave process has thus aided in the generation of a strong, wear resistant, durable carbon composite coating on aluminum 319 substrate.

1. Introduction

Laser shock processing (LSP) is an emerging process (Fig. 1) intended to generate shock waves and thereby induce compressive stresses within materials for the purpose of improving the mechanical properties such as hardness and fatigue strength [1]. LSP changes the microstructure and stress state without causing any heat damage or material removal; this is achieved by using single shot, nanosecond laser pulses of extreme intensity and absorptive layers on the surface. Laser power density on the material surface is chosen so high (of the order of 1–100 GW/cm^2) that optical breakdown occurs. Subsequent plasma generation and direct ablation of absorptive layer can produce recoil pressures in the gigapascal range. Confining plasma during its expansion by a dielectric medium (water or glass) strongly imposes the pressure waves on the substrate material. The rapid expansion of high-pressure plasma creates a shock wave that propagates through the material, creating dislocations and inducing plastic deformation. Thus the material experiences high strain/strain rates leading to major changes in the microstructure and improved surface properties such as hardness and fatigue strength.

Although LSP has been studied in metals like aluminum, its effect on deposition of coatings through shock consolidation has not been explored to a large extent [2,3]. LSP holds the potential to compact and densify discrete powders utilizing high amplitude stress waves [3]. It is also less cumbersome than explosive shock processing (ESP) that uses dangerous explosives to accelerate a plate that strikes and consolidates the powders. Furthermore, unlike ESP, LSP has better reproducibility and can be applied to non-planar surfaces and complex geometries.

In this work, LSP has been utilized to compact nanodiamond powders that were pre-sprayed on aluminum A319 and induce phase transition so as to produce a strongly adherent composite coating. The goal is to make aluminum more durable with less friction for applications such as engine components by exploiting nanodiamond's superhardness, chemical inertness, high wear resistance and high thermal conductivity. Nanodiamond (ND), also called nanocrystalline diamond or ultra-dispersed diamond, is emerging as a new type of material with better properties than single and polycrystalline diamonds due to its large surface area-to-volume ratio and electronic structure. ND powders are commercially available and are used in various applications including abrasives for the optical and semiconductor industries, durable and hard coatings, polymer reinforcements, lubricant additive for engines, protein absorbents and medicinal drugs [4].

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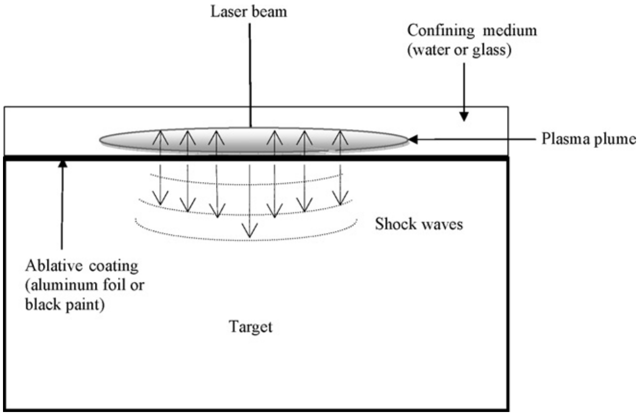

Fig. 1. A schematic of LSP process.

2. Experimental details

Aluminum 319 ingot was acquired from *Custom Alloy Light Metals*® Company (CA) with a nominal composition shown in Table 1. It is widely used in the production of automotive engine components due to its excellent mechanical and castability characteristics. The ingot was cut into smaller pieces, melted in an electric induction furnace at 1033 K and cast in a permanent mold. The cast rod was then heat-treated to T6 temper (age hardening) and sectioned into small disc samples of the size 25 mm diameter and 6 mm thick. Finally sand blasting was used to clean the rough spots and generate a good surface finish (R_a = 1.8 μm) suitable for coating.

Commercially available ND powder (4–8 nm), produced by shock detonation synthesis, was acquired from SPE SINTA Ltd., Kharkiv, Ukraine. Table 2 lists the powder characteristics with a guaranteed purity of 90%. Transmission electron microscopy images, shown in Fig. 2, confirmed the particle size range specified, indicated the particle shape to be closer to spherical and revealed 20–50 nm agglomerates. In addition, considerable amount of carbon onions surrounding the ND particles as well as amorphous carbon (note the selected area diffraction rings in Fig. 2) were observed. Infrared absorption spectrum indicated that the particle surface contained many functional groups (mainly carbonyl, carboxyl and hydroxyl) that were probably adsorbed during the powder synthesis.

Table 2
Characteristics of ND powders used in this work.

External kind	Powder of gray color
Moisture quantity (%) not more	0.5
Average size of prime particles (coherent scattering region) (nm)	2–8
Density (g/cm$^{3)}$	3.0
Quantity of metallic impurities (%) not more	2.0
Quantity of carbon cubic phase (%) not less	90
Quantity of impurity additives (%) not more	2.0

Prior to LSP, ND powders were sprayed on aluminum sample surfaces using an electrostatic gun. In this setup, the particles are negatively charged that follow the electric field lines toward the grounded sample resulting a pre-form with thickness of 30 ± 5 μm. The coating pre-form is loosely adhered to the sample by electrostatic forces. Since the diamond particles are very fine (~4–8 nm), agglomeration was an issue for achieving uniform deposition. To facilitate uniform deposition, a jet mill was integrated with the electrostatic spray deposition setup.

Three different laser shock experiments were conducted using a setup shown in Fig. 3. In the first set (Sample 1), a *Reynolds Wrap*® quality aluminum foil of 16.3 μm thick was pasted to the ND spray deposited sample using a thin layer of vacuum grease. Due to its relatively low threshold of vaporization, aluminum foil is said to act as an efficient ablative coating. The sample was placed in a glass beaker filled with deionized water (dielectric confining medium) that was 2–3 mm above the top of the aluminum sample. The height of the set up was adjusted using a Z-axis table such that the

Table 1
Nominal composition of alloy 319 used in this work.

	Element												
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Sn	Pb	Ni	Other	Al
Weight percent	5.860	0.678	3.519	0.246	0.056	0.104	0.901	0.160	0.021	0.032	0.121	<500	87.800

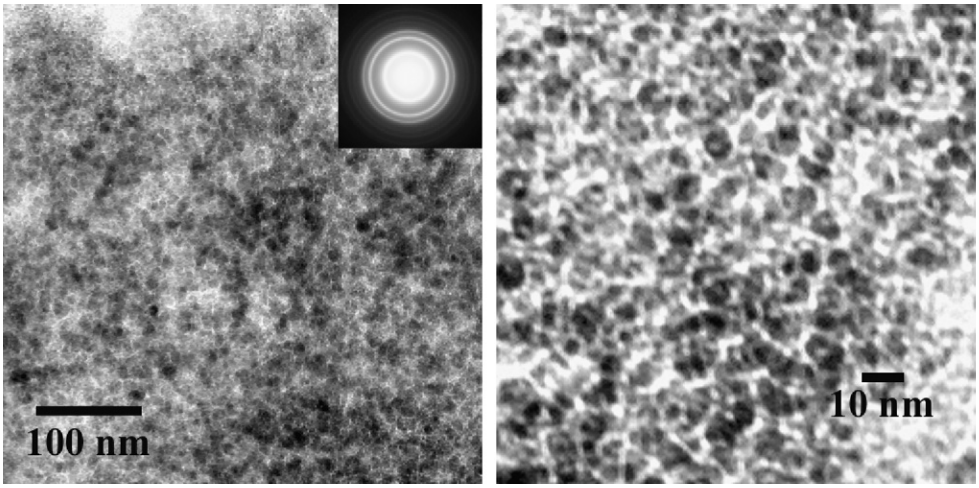

Fig. 2. Transmission electron micrographs of as-received nanodiamond powder.