Int. Journal of Refractory Metals and Hard Materials 53 (2015) 139–143

Contents lists available at ScienceDirect

Int. Journal of Refractory Metals and Hard Materials

journal homepage: www.elsevier.com/locate/IJRMHM

# Cold sprayed refractory metals for chrome reduction in gun barrel liners

Blake Barnett [a,*], Matthew Trexler [b,1], Victor Champagne [b]

[a] Oak Ridge Institute for Science and Education contractor appointed to the US Army Research Laboratory, 4600 Deer Creek Loop, Aberdeen Proving Grounds, MD 21005, USA
[b] US Army Research Laboratory Center for Cold Spray, 4600 Deer Creek Loop, Aberdeen Proving Grounds, MD 21005, USA

ARTICLE INFO

*Article history:*
Received 27 January 2015
Received in revised form 7 July 2015
Accepted 9 July 2015
Available online 17 July 2015

*Keywords:*
Tungsten
Alloys & composites
Spray coating
Thermal spray coating

ABSTRACT

Modern gun barrel technology faces a number of challenges related to the use of chrome-plated steel at the interior bore surface. The amount of allowable chrome has been significantly reduced due to environmental, health, and safety concerns. Furthermore, current munitions and propellants lead to erosion and condemnation of gun barrels well before their 10,000 round expected lifetime. This has precipitated a search for longer-lasting bore liners, such as refractory metals deposited by explosive bonding. The cost and difficulty associated with shaping these materials have made them impractical choices to date. Gas Dynamic Cold Spray consolidation of refractory metals and alloys was selected as an alternative to extrusion for additive manufacture of donor tubes. Tantalum–10 tungsten alloy donor tubes have been produced by cold spray and tested for compatibility with the cladding process. A 1-meter (3-foot) long tube was produced to test scalability.

## 1. Introduction

The liners typically used for the manufacture of gun barrels, selected for their low cost and relative ease of manufacture, are ill-suited to withstand the thermal cycling and hot gas corrosion caused by most propellants [1]. Chrome plating, long used as a surface coating to line and protect steel gun barrels, has been shown to provide insufficient protection for the expected lifetime of modern systems. Thermal cycling, hot corrosion, and mechanical wear all contribute to early wear and failure of chrome-based coatings, leading to the search for more durable materials. Moreover, mandates from environmental, health, and safety organizations such as the EPA for reduction of chrome exposure have made chrome unattractive for continued production [2]. Therefore, numerous research efforts [3–6] have been made to find suitable alternatives to chrome plating as a liner material that can offer extended gun barrel life and comparable or increased performance while maintaining competitive costs.

As munitions become more advanced, the trend has been towards higher energy rounds, which require higher temperature propellants that often produce corrosive exhaust. This has directed research efforts towards refractory based, high hardness alloys that will be able to withstand hot corrosion environments, thermal cycling, and the various stresses caused by compression cycles and erosion. The coating process is ideally also compatible with gun steel, demonstrating high adhesion, thermal protection, and the ability to integrate with current manufacturing processes and standards.

Refractory alloys possess many of the desired material qualities, but their high strengths present unique manufacturing challenges that can lead to high costs and long lead times. This has been especially true for tantalum-based alloys, which have been identified as materials of interest for scale-up testing by Benet Laboratories [7]. While one-foot sections of cold sprayed donor tubes had been investigated in other studies [8] for gun barrel linings, large scale (three feet or greater) testing had not been attempted. Benet Labs and ARL have collaborated to develop the capability and manufacturability of cold spray for the production of long Ta—10W donor tubes for evaluation as an alternate means of production.

## 2. Gas Dynamic Cold Spray

Gas Dynamic Cold Spray is a thermal spray type process that was issued a U.S. Patent in 1994 for coating applications [9]. Like thermal spray, cold spray directs powdered material towards a substrate in order to build up successive layers of particle “splats” from the impingement of the powdered material (Fig. 1). However, contrary to thermal spray, the cold spray process is designed to keep the powdered material in the solid state, and achieves particle splatting through the application of kinetic energy as opposed to thermal energy. The use of converging–diverging nozzles (DeLaval nozzles) along with high stagnation pressures results in solid particles moving at supersonic speeds (800–1200 m/s). At these speeds, upon impact with the substrate, the particles deform, mix mechanically with the substrate and each other, and form metallurgical and mechanical bonds. Through the application of successive layers of particles, a dense, highly adherent coating can be built to significant thickness. These coatings can serve in a number of applications, based on their composition and shape. Most notably for the present

---

* Corresponding author.
*E-mail address:* blake.d.barnett.ctr@mail.mil (B. Barnett).
[1] Present address: Under Armour, Inc., 1020 Hull Street, Baltimore, MD 21230, USA.

http://dx.doi.org/10.1016/j.ijrmhm.2015.07.007
0263-4368/

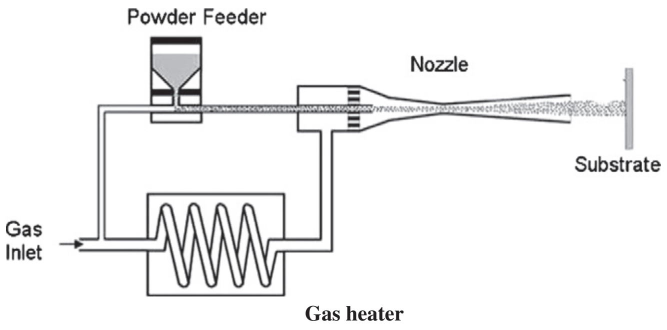

**Fig. 1.** Schematic of the Cold Spray Process.

work, careful design of the substrate and application of coating thickness can yield near net shape, additively manufactured parts with unique properties.

Due to the high strength and toughness of refractory alloys, conventional fabrication methods of production such as machining or extrusion can prove difficult and costly. Powder metallurgy approaches are often used with refractory alloys due to their reduced temperature requirements compared to ingot metallurgy; cold spray can be thought of as a type of impact-mediated sintering operation. However, due to the effects of the impact process, cold-sprayed parts typically have high ultimate strengths (near and sometimes beyond wrought strength) but low elongation. This is a direct result of the impact process, as particles essentially undergo 100% cold work as they form splats in the solid state. Resultant residual stresses are typically compressive [10,11] which can have repercussions on substrate geometry and as-sprayed material properties for near net shape applications.

## 3. Experimental procedure

### 3.1. Process modeling

A model previously developed by Champagne et al. [12] was used to predict the powder size(s) required and optimum cold spray parameters of Ta–10W alloys and blends based on prior work with pure tantalum [8]. The model relies on assumptions based on material properties such as density, modulus and yield strength and has been used to accurately predict the deposition efficiency (DE, a measure of process waste) of copper and aluminum particles as a function of particle size. Investigations were also made into the effects of using nitrogen as a process gas as opposed to helium. Fig. 2 shows the calculated DE for Ta–10W using helium and nitrogen as a function of pressure. Due to the greater mass of molecular nitrogen compared to helium, higher pressures are required when using nitrogen to achieve the same particle velocity (and thus the same deposition efficiency). However, it should be noted that this calculation does not account for the physical properties of the deposit, such as residual stress or porosity. Although helium was used for this particular study, the potential for comparable efficiencies with nitrogen shows promise for additional cost savings in the future. Deposition efficiency is calculated as a function of cold spray nozzle inlet parameters, and subsequently verified experimentally. Using an isentropic gas flow and associated particle drag models (described below), highly efficient spray parameters can be selected to yield DE's greater than 80%, which is particularly critical when using high cost refractory feedstocks. The DE model enables pre-selection of cost-effective process parameters while reducing the need for multiple iterations of time and feedstock intensive spray trials.

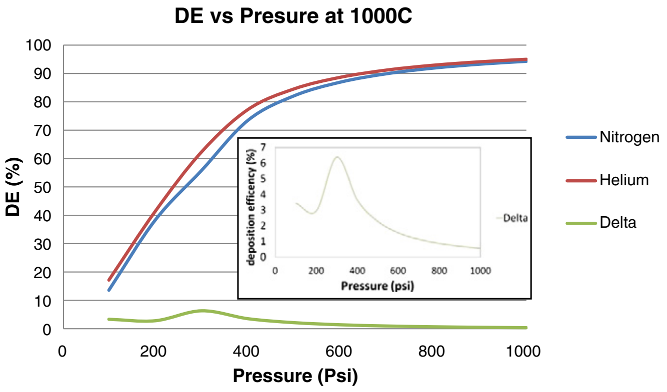

**Fig. 2.** DE model as a function of temperature for Ta–10W at 1000 °C.

Deposition efficiency is calculated as a function of Mach number, temperature, and pressure at the inlet of the cold spray nozzle, which is then iteratively used to calculate gas velocity along the nozzle, through the gas exit from the nozzle and its impact with the substrate with associated bow shock. Particle size, size distribution, and shape are used to calculate particle velocity as a function of drag and heating in the gas stream, and a fraction of the particle population that will impact the substrate at or above the critical deposition velocity is calculated assuming a log normal size distribution around a user-supplied mean particle diameter. The critical deposition velocity is given by the formula from Assadi et al. [9]:

$$v_{ct} = 667 - 14\rho + 0.08T_m + 0.1\sigma_u - 0.4T_i \tag{1}$$

where $\rho$ is the material density in g/cm$^3$, $T_m$ is the melting temperature in °C, $\sigma_u$ is the ultimate strength in MPa and $T_i$ is the initial particle temperature in °C. These parameters summarize the onset of adiabatic shear instability in the impinging particles.

Particle velocities as a function of gas flows are determined using 1-d isentropic gas dynamic equations for gas stagnation conditions in a given nozzle geometry (inlet, throat, and expansion areas), as well as beyond the nozzle and through the bow shock preceding the substrate. Once gas conditions and velocity are characterized within and beyond the nozzle, particle velocity is iteratively calculated down the length of the nozzle through the use of a solid rocket nozzle particle drag relationship:

$$m\frac{dV_p}{dt} = C_D(\pi/8)\rho_g d^2 (V_g - V_p)^2 \tag{2}$$

where $V_p$ and $V_g$ are particle and gas velocities, m is the particle mass, $\rho_g$ is the gas density, and d is the particle diameter. Additional considerations are made for particle heating in the gas stream through the application of a gas-particle heat transfer under forced convection:

$$c_p\frac{dT_p}{dt} = (N_u k/d)(A_p/m)(T_g - T_p) \tag{3}$$

where $c_p$ is the particle heat capacity, $T_p$ and $T_g$ are the particle and gas temperatures, $N_u$ is the Nusselt number, k is the gas conductivity, and $A_p$ is the particle surface area. Values for either Nitrogen or Helium can be used depending on the process gas to be used for deposition.

These particle velocity, temperature, and material property inputs are used iteratively prior to cold spray to calculate initial process parameters, which are optimized to yield a maximum deposition efficiency as shown in Fig. 2. The resultant deposits are then characterized to evaluate coating quality with respect to performance criteria such as porosity, density, and hardness. Typical process parameter development cycles balance maximum DE, which typically occurs at the highest gas temperatures and pressures, against various processing issues, such as coating costs, residual stress from overworking of deposited particles, the erosion velocity of the particles for the substrate in question.