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SPECIAL FEATURE

Low pressure cold gas dynamic spraying of tungsten carbide-nickel coatings

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The use of cold gas dynamic spraying to produce tungsten carbide based coatings has increased over the past decade [1–8]. Powders may be accelerated to high speeds to produce thick, dense coatings, comparable to some coatings produced using high temperature deposition methods. In the absence of high temperatures, during cold spray, severe plastic deformation of the powder particles are required to ensure good adhesion to the substrate.

This is readily achieved when ductile metals such as Ni, Cu, Co and Al are deposited. However WC – which is a hard, brittle material – does not undergo plastic deformation and must therefore be co-deposited with a ductile binder to produce WC-based coatings.

Majority of the published cold spray research undertaken uses high pressure systems, while there is limited research available on the use of low pressure cold spray systems to produce hard coatings. While it has been shown that material properties are generally better when using high pressure systems, there are several advantages or benefits to using low pressure systems. The use of low pressure cold spraying is deemed to be economical and versatile, and has been deemed safe and easy to automate. It may also be employed as a portable system to conduct on-site repairs, similar to the use of portable welding machines. The low temperatures and pressures used also ensure that the system is energy efficient, which in certain parts of the world are critical. In the current paper a summary of the research undertaken in our research group to produce WC-Ni coatings using low pressure cold gas dynamic spraying is given.

Cold spray deposition methodology

In all the research undertaken to date, a low pressure cold spray machine, Centreline Series P SST, is used with a Comp Air external air compressor having a maximum capacity of 10 bars (150 psi). A convergent–divergent De Laval nozzle with a length of 120 mm, an entrance and exit diameter of 2.5 mm and 6 mm, respectively, is used to transmit the powders to the substrate. An integrated, dual-hopper, non-pressurized vibratory powder feeder with variable feed rate settings is used to introduce the powder particles to the moving air stream. The gun transverse speed is generally fixed and the spraying motions of the 3 axis-robot are kept constant. Temperature, stagnation pressure and standoff distance are the operating parameters typically varied. The Taguchi mixed level design of experiments [9] is generally used to find the optimal spray parameters for each powder blend. An example of how this method was applied in one project may found in Ref. [10].

Prior to cold spraying, the substrates are grit blasted with alumina to improve coating adhesion. Some researchers have claimed that smoother surfaces may provide better coating properties, but this has not been tested in our research. The embedment of blasting media in the substrate surface continues to be problematic despite the use of extensive ultrasonic cleaning. While this technique ensures a clean surface, the remaining grit particles influence coating adhesion and possibly deposition dynamics. It may be good to consider alternative 'grit-free' methods to induce the required level of surface roughness in substrates. The question of an 'optimum' or 'required level' of surface roughness is an open one.

Research summary

Initial studies on the deposition of WC-Ni coatings was done by blending WC and Ni powders, as well as blending WC-12 wt%Co agglomerated and sintered powder with Ni powder [10]. The Ni

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content was varied between 4 and 50 wt% and a Taguchi mixed level design of experiments method was used to optimize the spray parameters. All coatings had low porosities, no decarburization, and typically a non-homogenous distribution of the WC phase was observed. The morphology of the starting powders was found to influence the microstructure of the coatings produced. The agglomerated and sintered WC-Co powders had a spherical and porous structure which tended to elongate during deposition. The dense, angular oxide reduced WC powder showed increased fracture of individual carbide grains, but produced denser coatings compared to the WC–12 wt%Co–*x*Ni blends. However the amount of WC retained in the coatings was higher when using the agglomerated and sintered WC–12 wt%Co powder, with a maximum of 74.08%WC being retained for the WC–12 wt%Co–4 wt%Ni composition. For both coating blends, the amount of WC retained decreased as the Ni content in the starting powders increased. This is in agreement with Melendez et al. [1]. Despite the higher carbide retention, the WC–12 wt%Co–*x*Ni coatings had lower hardnesses compared to the WC–*x*Ni coatings.

The feasibility of producing a hard, wear resistant coating which could be applied to iron-based materials for surface repairs was investigated by blending WC powder (90 wt%) to a Ni–Al–Al_2O_3–Zn powder blend (10 wt%), typically used in the repair of cast ion components [11]. Fairly dense coatings with good adhesion having a WC retention of approximately 47% were produced. The WC particles were homogeneously distributed throughout the coating which ensured uniform coating properties were achieved. Friction and dry sliding wear tests were conducted using a micro-tribometer under applied loads of 5 and 10 N. The steady state friction coefficient ranged from 0.33 to 0.64, while the average wear rate increased from 3.04×10^{-5} to 6.15×10^{-5} mm^3/Nm for the 5 N and 10 N applied loads, respectively. The worn surfaces showed plastic deformation of the binder, WC and alumina grain cracking and fragmentation, as well as grain pull-out. Groove formation parallel to the direction of sliding and adhesion of the wear debris was also evident.

The wear properties of WC–Ni coatings were further explored by adding TiC and Mo, and conducting wear tests under slurry abrasion and dry sliding wear conditions [12,13]. Four coating compositions were investigated namely WC–4 wt%Ni, WC–4 wt%Ni–1 wt%Mo, WC–4 wt%Ni–10 wt%TiC and WC–4 wt%Ni–10 wt%TiC–1 wt%Mo. Both TiC and Mo are well known additions to WC alloys which improve hardness, wear and corrosion resistance [14]. All four compositions produced dense coatings having low porosities (<1%), and averaged 40 wt% retention of WC. Only 4 wt% of the TiC was retained in the coatings. As TiC is a hard carbide, it also experiences the same deposition characteristics which WC is known to experience during cold spraying, i.e. fractures during deposition, and the tendency to bounce off rather than adhere. The expected increase to hardness was not realized, and the WC–4 wt%Ni coating was the hardest one produced averaging 500 $HV_{0.3}$. The XRD patterns of the coatings confirmed that no decarburisation occurred and no phase changes were experienced. For the slurry abrasion testing two different slurry mediums were used, namely a silica-distilled water slurry and a silica-synthetic mine water slurry [15]. The first slurry was used as a control against which the aggressiveness of the mine water slurry could be assessed. The WC–4 wt%Ni coating had the best wear resistance against both slurries. When TiC and Mo was added, the abrasion wear rates more than doubled in some instances. The wear mechanisms were similar to those typically observed for cemented tungsten carbide materials when subjected to abrasion [16]. The angularity of the hard silica particles facilitated the preferential removal of the softer nickel binder phase from between the carbide grains, which left the carbide grains unsupported making their removal easier as abrasion proceeded. Some of the removed material acts as hard micro-abrasives which then subject the coating to additional wear, and caused fracture of the embedded carbide grains. The same coatings were subjected to friction and dry sliding wear tests using a micro-tribometer under applied loads of 5 and 10 N and a 100Cr-steel ball as the static partner [13]. The steady state friction coefficients ranged from 0.65 to 0.8. The wear rates of the coatings decreased as the applied load increased, which does not follow the typical trend of increasing load leading to increased wear. The wear mechanisms were those typically experienced by hard carbide coatings under sliding wear conditions, with grain pull-out and fragmentation and selective binder removal and smearing.

The type of substrate used influences the coating properties. A study has been done to compare the properties of WC–Ni coatings deposited onto mild steel and stainless steel substrates [17]. Differences were observed in the coating hardness, porosity, WC grain size and Ni binder mean free path. There was also a difference in the adhesion characteristics of the coating to the two metals, with a greater degree of mismatch being experienced for mild steel. The influence of powder feed rate on the mechanical properties of a WC–Ni coating was investigated [18]. The results showed that an optimum volumetric feed rate exists to produce a dense coating, wherein a high level of Ni plastic deformation is achieved, along with the retention of a fair amount of WC particles. The WC feedstock powder used in the study had a particle size distribution of $-0 + 4$ μm, which is much finer than the powders used in previous studies ($-45 + 5$ μm). This led to less fracture being experienced by the WC particles during deposition, and the particles are too small to cause significant erosion during impact. The optimum feed rate produced coatings which had the best microstructural properties in terms of porosity, WC grain size and Ni binder mean free path, and the best mechanical properties in terms of hardness, toughness and strength.

Challenges

Although good results are being achieved thus far for WC–Ni coatings using low pressure cold spray deposition, there are still challenges to address. The low retention of WC particles in the coatings is problematic and ways need to be found to increase the retention in order to provide coatings which can endure industrial operational conditions and which have reasonable service lives. The low retention of the carbides also means that a significant amount of powder is being wasted during deposition, and considering the high cost of WC powder this problem needs a viable and cost effective solution. There are techniques available which may be used, such as mechanical alloying of the powders, or coating the WC powder particles with the binder prior to deposition. In the deposition process itself, the process variables can also be changed such as temperature, gas type and pressure. However if these parameters are increased too much, then the process may no longer be considered a low pressure cold spray system, and the feasibility of using the technique as a cost effective, portable, onsite tool decreases.

A second challenge is the WC feedstock powder morphology. It is well known that particle morphology plays a significant role in the deposition process, including adhesion characteristics [19,20]. Currently there is a variety of metallic powders which have been manufactured specifically for use in cold spray deposition and seem to provide excellent coatings. However the WC powders currently being produced do not appear to have the required spherical morphology and associated properties which are believed to be better suited to cold spray deposition, and should theoretically allow for greater retention of carbide in the coating. While this technique is generally considered a coating deposition process, cold spray technology is also finding application in additive manufacturing. Perhaps with the advances being made in the additive manufacturing sector which also require specific powder characteristics, the manufacturing of WC powders suitable for both processes will advance as well.

A third challenge is the adhesion of the cermet coatings to the metallic substrates and adhesion of subsequent coating layers during deposition. While the Ni binder adheres well to the substrate and coating layers due to the plastic deformation it undergoes, the WC particles do not plastically deform, and adhesion becomes problematic. The WC particles have a greater tendency to fracture and erode both the substrate and coating layers. Using finer WC feedstock powders may be a solution, but the powder particle morphology would also need to be improved.

Despite the three challenges mentioned above, the mechanical and wear properties of WC–Ni coatings produced using low pressure cold spraying seems to be on par with some of the high temperature coating processes, and in some cases achieving superior properties.

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