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Design and Production of Powders Tailored to Cold Spraying

1. Introduction

There are number of well established high temperature thermal spray processes in use today e.g. Plasma Spray and HVOF, however there are a number of deficiencies associated with them. Oxidation, phase transformations and crack formation can occur during the process of melting and subsequent rapid solidification of the sprayed material on the substrate, adversely affecting the quality and performance of the coating. In order to overcome these issues Cold Spray coating technology has been developed which is able to produce high density coatings whilst avoiding the issue of oxidation.

In this paper we provide an overview of gas atomising for manufacture of metal powders for Cold Spraying. The gas atomisation process is described and the relationships between the powder characteristics and finished coating quality are discussed: factors which underpin the advantages that Cold Spray offers over conventional thermal spraying processes.

2. The Gas Atomisation Process

Sandvik Osprey has been utilising proprietary gas atomising technology for over 15 years to manufacture a wide of alloy powders that are used in a diverse range of applications including metal injection moulding (MIM), rapid manufacturing, thermal spray and, more recently, cold spray.

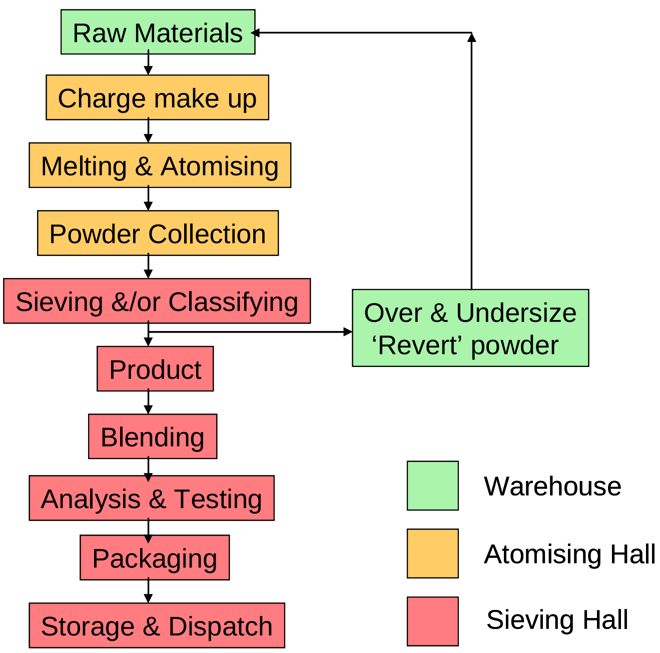

Figure 1: Flow diagram of the gas atomisation process

Figure 1 shows a flow diagram which provides a description of the main steps in the gas atomisation production process. Raw materials, in the form of virgin metals, scrap or ferroalloys are charged into a refractory lined furnace and melted by electrical induction. The source and composition of the raw materials used are fully traceable throughout the production process. The furnace is itself protected by an inert gas shroud which minimises the pick up of atmospheric gases during the melting process. Once molten the metal is then poured into a tundish with a ceramic nozzle at one end. The metal flows through the nozzle and as it exits the molten stream is impacted by high pressure gas, disrupting the liquid stream and forming a spray of molten droplets. These droplets cool and solidify to form discrete powder particles as they fall under gravity to the bottom of the atomising chamber, where they are separated from the atomising gas and collected in a clean, dry container. Nitrogen is typically used as the atomising gas, however argon can also be used when processing alloys with reactive components e.g. aluminium or titanium in order to minimise the formation of impurities such as nitrides.

The next step in the process is to extract the required particle size fraction from the 'as atomised' powder size distribution. This is achieved using sieving or air classification depending on the size fraction required. Sieving can be used to separate particles down to 32 µm in size whilst air classifying must be used to separate smaller particles. The popular sizes used in cold spray today e.g. -38 +15 µm or -32 +10 µm require both sieving and classification whilst -25 +5 µm powders must be classified twice.

Once the required particle size distribution has been obtained both the chemical composition (using ICP/OES) and particle size (using a Malvern laser diffraction system) is tested to confirm that the powder is within specification. Finally the powder is packaged ensuring that the quality and condition of the powder is maintained before use.

3. Gas Atomised Powders for Cold Spray

3.1 Characteristics of Gas Atomised Powders

The inherent characteristics of gas atomised powders make them ideally suited for cold spray applications. Figure 2 shows an SEM image of a typical 'fine' gas atomised stainless steel powder.

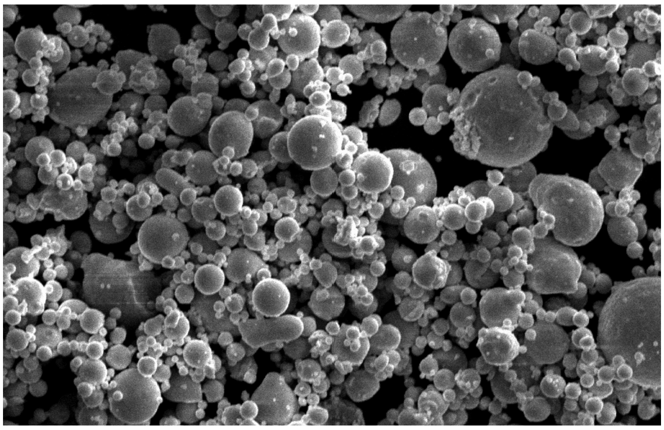

Figure 2: SEM image of fine gas atomised powder

Fukanuma et al. [1] identified that powder morphology can have a significant influence on the velocity that the particles reach during cold spraying. Gas atomised particles are characterised as having a spherical morphology, giving the powder good flow characteristics. In comparison, water atomised powders which are today used widely in conventional thermal spray applications, have worse flow properties due to their irregular shape.

Another important characteristic of gas atomised powders is their low oxygen content. Whilst water atomised powders have an intrinsically high oxygen content (typically several thousand parts per million) which originates from the atomising medium itself, careful control of key process variables during gas atomising will produce a powder with a significantly lower oxygen content as shown in the following table.

Alloy	Oxygen Content (ppm)	
	Average	Standard Deviation
17-4PH	700	150
316L	660	100
420	460	130
Co28Cr6Mo	250	70
Fe7Si	460	50
440C	490	140
4340	380	150

Table 1: Typical Oxygen levels in fine gas atomised metal powders manufactured by Sandvik Osprey

There is an increasing body of evidence that demonstrates the advantages of using powders with low oxygen contents in cold spraying. Zimmermann & Eiling [2] found that the use of a low oxygen, spherical gas atomised nickel powder for cold spray products resulted in both improved deposition efficiency and a higher density coating compared to an equivalent water atomised product.

Much of the early development and optimisation of the cold spray process was carried out using copper powder, as in the work of Kreye et al. [3], and here the benefits of low oxygen powders are again apparent. Li et al. [4] have shown that the critical velocity required for bonding is directly proportional to the powder oxide content. Kairet et al. [5], found that a deposition efficiency of approximately 80% was realised using a gas atomised copper powder with an oxygen content of 500ppm, compared to only 60% when the powder used had an oxygen content of 1720ppm. They also observed that, in the case of the powder with 500ppm oxygen, the oxide content of sprayed coating was only 20% higher than that of the starting powder. In the case of the powder with 1720ppm oxygen, however, the oxide content of the final coating was some 80% higher .This will in turn lead to an increased risk of cracking at the coating interface and therefore have a negative impact on the coating performance.

The influence of powder surface oxygen content on the performance of other alloy families in cold spraying has also been investigated. Li et al. [4] demonstrate that the surface oxygen content of the powder can have a significant impact on the critical velocity of both 316L stainless steel and Monel (nickel copper) alloy.

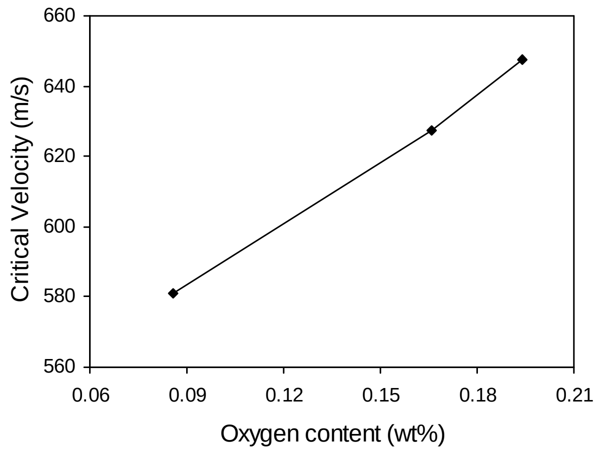

Figure 3: Effect of oxygen content of 316L stainless steel powder on its critical velocity for deposition in cold spraying. Li et al. [4]

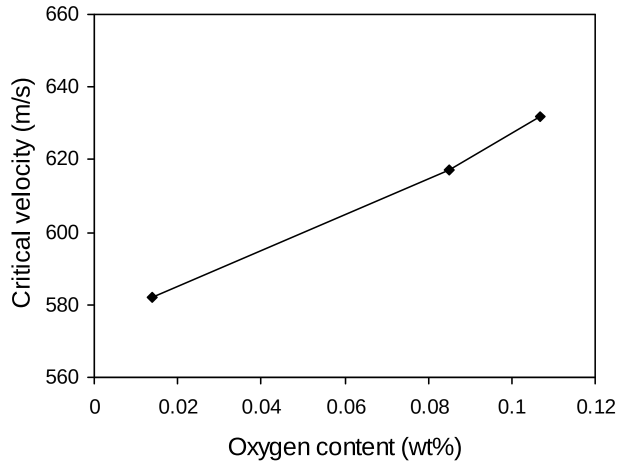

Figure 4: Effect of oxygen content of monel powder on its critical velocity for deposition in cold spraying. Li et al. [4]

Examination of the data shown in Figures 3 and 4 reveals that a reduction in the oxygen content of 316L powder from 1660ppm to 860ppm results in a reduction of critical velocity by approximately 8%, whilst a reduction in the oxygen content of monel powder from 850ppm to 160ppm results in a reduction of critical velocity by approximately 6.5%. The median particle sizes of the 316L and monel powders used were 9.6µm and 20.8µm respectively. Examination of the data contained in Table 1 indicates that the average oxygen content of fine 316L gas atomised powders manufactured by Sandvik Osprey is 660ppm, which would infer a further reduction in critical velocity below 580 m/s.

3.2 Quality requirements and availability of powder for cold spray

In the previous section both powder morphology and oxygen content have been identified as characteristics that have a significant influence on the performance of powder in cold spraying. In addition to these two parameters a theoretical analysis of the cold spray process reveals that there is an optimum size range requirement for the powder [6]. Sandvik Osprey's experience that 'fine' powders i.e. powders with a diameter of less than 38 µm are used extensively for cold spraying today.

Size Range (µm)	Separation Method
-38 +15	Sieving + classification
-38 +10	Sieving + classification
-32 +10	Sieving + classification
-25 +5	Classification

Table 2: Range of commercially available particle size distributions for Cold Spray

The data contained in table 2 would suggest that there is no one ideal particle size distribution for all of today's cold spray applications. Indeed, the work of Makinen et al. [7] demonstrates that the optimal particle size for successful bonding is dependent on the coating material itself. This work also identifies that the spraying parameters used have an influence on the quality of the coating, such that every powder type requires a customised set of processing parameters to achieve the best quality coating. This illustrates clearly why it is imperative that cold spray companies work closely with powder manufacturers to deliver the best overall solution.

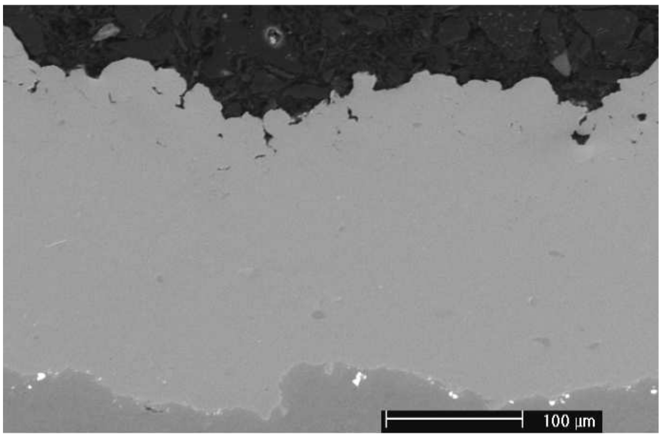

Figure 5: High Pressure cold sprayed (HPCS) Ni-30Cu coating on grit-blasted steel substrate, using -38+16 µm gas atomise powder from Sandvik Osprey, Koivuluoto et al. [8]

Sandvik Osprey has five atomising plants, three of which are specifically designed for the manufacture of 'fine' powders as used in cold spraying. These three units have varying capacities that support all stages of the development cycle, from 20kg experimental lots for initial testing through to high volume production lots of 3000kg. The plants utilise proprietary atomising technology developed by Osprey to maximise the yield of fine powders that is achieved and thereby optimise product costs.

Type	Alloy	Composition
Pure Metals	HC Copper	Cu 99.9% min
	OFHC Copper	Cu 99.95% min
	Tin	Sn 99.0% min
Binary Alloys	Fe-Ni	1-50% Ni
	Fe-Co	1-50% Co
	Fe-Cr	1-50% Cr
	Fe-Si	1-45% Si
	Ni-Cr	1-50% Cr
	Ni-Cu	1-30% Cu
	Cu-Sn (Bronze)	1-50% Cu
	Cu-Al	1-20% Al
Stainless Steels	Austentic, ferritic etc.	304L, 316L, 430L, 440C
Other types	Ni based, Co based, Cu based	In625, In718

Table 3: Example alloys available for Cold Spray applications

Table 3 contains an overview of the different alloy families that have been supplied for evaluation in cold spray applications to date. Whilst pure metals such as copper and tin represent a significant proportion of overall cold spray powder sales, the demand for other alloys appears to be growing. A good example of an industrial application using cold sprayed ferrtic stainless steel is in the manufacture of aluminium-cast cookware by obz innovation gmbh. By coating the bottom of the cookware with a layer of magnetisable stainless steel it allows the pans to be used the on modern induction cookers.

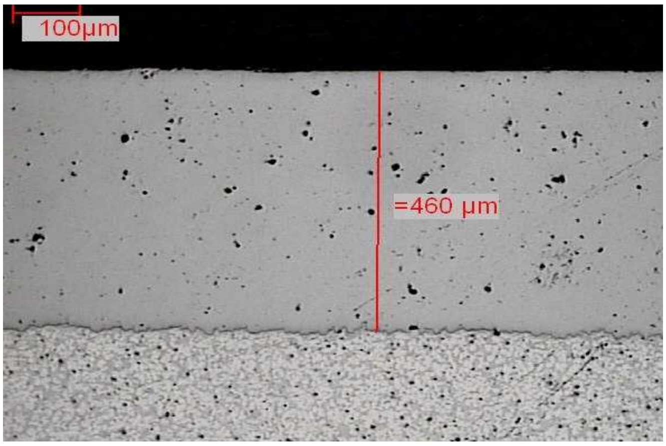

Figure 6: Cross section of ferritic stainless steel coating applied by High pressure cold spray by obz innovation gmbh.

In the case of copper there is also a trend towards the use of lower oxygen powders, driven both by desire to apply higher quality and more cost effective coatings. Sandvik Osprey has a proven track record in the manufacture of high quality copper powders. Driven initially by demand from the MIM industry, both High Conductivity (HC) copper (oxygen content 3000ppm max) and Oxygen Free High Conductivity (OFHC) copper powder (oxygen content 1500ppm max) have been part of Osprey's product offering for a number of years. Use of these powders in the manufacture of thermal management components via MIM has been shown to deliver good levels of thermal conductivity in the final sintered parts [9]. More recently the level of enquiries for copper powders with even lower oxygen levels has increased significantly, driven primarily by the cold spray segment. In response to this market demand Sandvik Osprey has developed a copper product with an oxygen content of 500ppm specifically designed for cold spray applications.

4 Summary and Conclusions

The type of powder used in cold spraying can have a significant effect not only on the quality of the final coating but also on the economics and efficiency of the coating process. Particle morphology, oxygen content and particle size distribution are three important parameters that determine the suitability of powders for cold spraying. Gas atomised metal powders are characterised as having both a spherical morphology and low oxygen content, as compared to water atomised powders which are irregular in shape and have high oxygen content. The characteristics of gas atomised powders make them ideally suited for use in cold spray processes. Sandvik Osprey has a well established track record in the supply of fine gas atomised metal powders into a number of high end applications and is actively looking to work in partnership with cold spray customers to develop and customise new alloys for their specific requirements.

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