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# Influence of thermal properties and temperature of substrate on the quality of cold-sprayed deposits

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ABSTRACT

The properties of cold-sprayed deposits are often considered to depend mainly on the particle velocity and the particle temperature. The present paper demonstrates, through systematic experimentation and multi-scale modelling, that the substrate properties, too, influence the deposit properties, even in the regions far away from the substrate/deposit interface. Cold spraying experiments were performed with copper and titanium powders, using fixed process parameters, but different substrate materials and different substrate temperatures. As a measure of coating quality, the electrical conductivity of the coatings was evaluated on the top surface of (0.8–1 mm) thick coatings. The coating conductivity was found to depend strongly on the initial temperature and the thermal effusivity of the substrate. The mechanical properties of the substrate, also, influence the local coating properties, but only in the regions within 50 μm distance from the substrate/coating interface. The temperature and the thermal effusivity of the substrate control the instantaneous temperature of the top surface layer of the already deposited material, thus influencing the extent of particle bonding and the coating properties. These findings underline the role of thermal management in cold spraying.

## 1. Introduction

Cold spraying is a solid-state coating process, in which material deposition takes place by high-velocity impact, severe deformation, and bonding of microparticles [1]. Like explosive welding, deformation in cold spraying is associated with adiabatic shear instability (ASI) and large plastic deformation at the contact area [2–5]. The critical velocity of bonding – i.e. the minimum particle impact velocity required to create bonding – depends on various factors, most importantly on the temperature and the thermomechanical properties of the respective particle and substrate materials [2,6]. The main coating properties have been shown to be a unique function of the ratio of particle velocity to critical velocity, here referred to as $\eta$ [7]. Many previous studies have aimed to understand bonding mechanism, to evaluate the critical velocity, and hence $\eta$, for different materials and process conditions [4,7–18]. So far, none of the suggested formulae for the critical velocity and $\eta$ incorporate substrate properties.

In cold spray deposition, there are two distinct types of interaction that should be distinguished from one another: (i) particle-to-substrate interaction, which is necessary for the formation of the first layer of particles, being relevant for the adhesive strength of the final coating on the substrate, and (ii) particle-to-particle interaction, which concerns the build-up of the coating, and relates to the cohesive strength of the deposit [19,20]. This means that the critical velocity for the deposition of the first layer of particles may be different from that of the next layers, particularly for the case of dissimilar coating and substrate materials [20–22]. For dissimilar materials, therefore, the cohesive strength of a cold-sprayed deposit may be rather different from the (adhesive) bond strength between the coating and the substrate. While the latter can be influenced significantly by the substrate material, temperature and surface conditions, the former might seem to be independent of the substrate-related factors [3,8,15,19–30]. This is in fact not true. As will be discussed later, there are indications of the influence of substrate type and conditions not only on the adhesive strength, but also on the cohesive strength, electrical conductivity, and the related 'bulk' properties of the cold-sprayed deposits, even at regions far (hundreds of microns) away from the substrate/

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coating interface [20,22,23,29,31,32]. This might seem somewhat surprising, because the coating properties – such as the cohesive strength – are conceived to be influenced by the second type of bonding (particle-to-particle) as explained above. In other words, it is not clear how the substrate conditions can influence particle-to-particle bonding within the coating, particularly in regions that are 'isolated' from the substrate by several layers of the already deposited material.

Despite indications of strong substrate effects, most cold spray studies have focused on the effect of process parameters – such as gas pressure and temperature – on coating characteristics [17,33–38]. Also, much attention has been paid to the formation of the first layer, and hence, on the adhesion of the coating to the substrate. For instance, it has been shown how the hardness and temperature of the substrate may influence the adhesion strength [19–32,39,40]. The effect of substrate hardness on adhesion strength may be interpreted in view of particle-substrate interaction – type (i) as mentioned above. Harder substrates make impacting particles deform more severely, whereas softer substrates result in smaller deceleration and hence less severe particle deformation [8,19–23,41]. On the other hand, softer substrates deform more severely under particle impact, which could result in ASI on the substrate side and hence promote bonding. For cold spraying of copper, for instance, the value of bond strength for aluminium and copper substrates are about four times higher than that for the low carbon steel substrates [42]. It is also shown that substrate preheating generally increases the adhesion strength and the deposition efficiency of the first layers [25–27,29,39].

Examples of studies that indicate the effect of substrate material on the coating properties are given in Refs. [20,22,23,29,31,38]. (Note that the coating properties concern type (ii) interaction as mentioned above.) For example, tensile strength of cold-sprayed titanium coatings was shown to be 20% higher for 304 stainless steel (EN 1.4301) substrates as compared to AlMg3 substrates [38]. Moreover, the strength of copper coatings nearly doubled when cold spraying was on steel substrates as compared to when it was on copper substrates [29]. There are also numerical investigations with different combination of materials, showing that substrate hardness may affect coating performance, but this was demonstrated only for a case where the coating was relatively thin [41]. Several investigations [25,31,32,39] suggest that substrate temperature can influence the deposition efficiency, e.g. in bulk metallic glasses. Improved coating properties – strength, cavitation resistance or conductivity – could be obtained by substrate preheating in cold spraying of copper [29] and bronzes [43]. Conversely, there have also been studies that show no obvious effect of the substrate temperature on the coating porosity, microstructure, or hardness, e.g. in cold spraying of copper and aluminium [26,44]. This discrepancy could have resulted from differences in the employed method of substrate heating in different studies. In one group of experiments, low power heaters are used, so that the substrate temperature is initially high but it is substantially reduced because of cooling by the gas stream during the spray process [31,44]. In another group of experiments, high power controls are used, which guarantee constant substrate temperature during the whole process [29,43]. In any case, whether or in what sense the substrate temperature affects the coating quality has remained an open question.

It should also be noted that substrate hardness decreases with increasing temperature. Therefore, it may seem that substrate preheating affects coating properties merely via thermal softening of the substrate. It is nevertheless not clear how a change in the mechanical property of the substrate can influence type (ii) interactions, especially in regions far away from the substrate. In summary, the influences of the type of substrate material and the substrate temperature on coating properties call for further investigations. The present work aims to look into this problem by combining systematic experimentation with modelling at different length scales. Here we focuse on the following specific questions:

1. Does the substrate effect – on type (ii) interactions – exist? In other words, is there an influence of the substrate conditions – such as dimensions, material properties and the initial temperature – not only on the adhesive strength, but also on the properties of cold-sprayed deposits? If so, what are the influential factors and how do they influence these properties?
2. Where does the substrate effect, if present, originate from? How can the substrate 'communicate' its properties to the deposited material in locations far away from the coating/substrate interface? What substrate properties, i.e. mechanical or thermal, are more relevant? How can the substrate effect be predicted and controlled?

To answer the first set of questions, a series of experiments have been designed and carried out, in which properties such as the hardness and electrical conductivity of the cold-sprayed coatings have been evaluated for the same spraying conditions, but different substrate materials and initial temperatures. For this purpose, the ultimate tensile strength (UTS) as obtained using the micro flat tensile (MFT) test may be considered to be a most suitable property. The MFT test result is a reliable measure of the coating quality, e.g. as demonstrated for copper coatings [6,45]. However, MFT test is restricted to relatively thick coatings and is therefore not always straightforward to implement. Alternatively, the electrical conductivity of a coating may be used to obtain information on the coating quality, as well as on the level of defects and impurities such as oxygen or nitrogen [29,46]. The measurement of electrical conductivity, using the eddy current method, is based on the analysis of electron mobility in plane of the coating layers. For cold sprayed titanium coatings [47], a strong correlation exists between the electrical conductivity and the UTS, as obtained using the MFT test, Fig. 1. Both quantities are highly anisotropic, but in this case, they correspond to the same (in-plane) direction. In view of the above correlation, the electrical conductivity is used in the present study as a convenient measure of the coating quality, and so, of the extent of bonding between adjacent particles within the coating [32,46,48] – pertaining to type (ii) interactions.

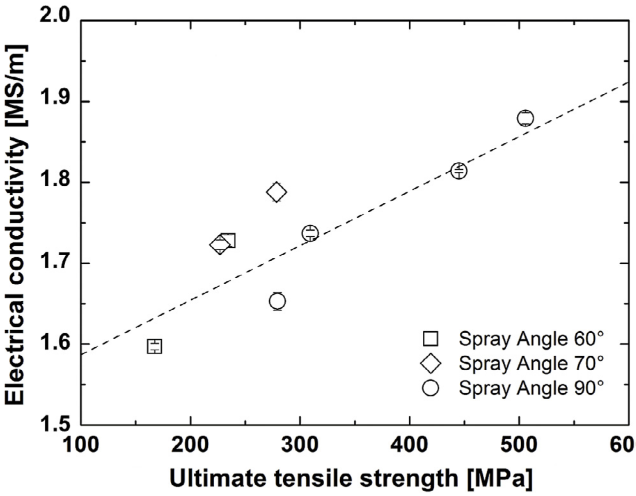

**Fig. 1.** The correlation between electrical conductivity and in-plane ultimate tensile strength of cold-sprayed titanium coatings, as obtained for different spray angles and nozzle geometries. Data from Ref. [47].