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Systematic analysis of coating-substrate interactions in the presence of flow localization

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ABSTRACT

Localized deformation and cracking in a system of thermally sprayed hard metal coating overlaid on a low alloy steel is studied by means of bend testing. In-situ digital image correlation measurements are used to characterize material strain field near the coating/substrate interface. The studied substrate undergoes softening upon yielding which manifests itself as narrow bands of localized shear deformation. The measurements show that the coating cracks and the substrate shear bands interact. When the coating starts cracking during the elastic loading of the substrate, the formed cracks function as nucleation points for the shear bands. In contrast, if the coating resists cracking until the yielding of the substrate, the coating cracks and substrate shear bands form simultaneously. Based on the experiments, continuum-scale finite element model of the system is developed, validated and then used for a systematic numerical analysis of the effects of substrate shear banding on the measurement of coating properties. Based on the results of this work, three main effects can be identified. Firstly, the flow localization in the substrate can increase the measured apparent (macroscopic) surface strain of the coating, if not accounted for by using microscopic techniques. Secondly, substrate shear bands increase the interfacial loading, which may cause unexpected delamination of the coating and thus affect the evaluation of the interfacial strength. Finally, substrate shear bands affect the stress state within the coating and may thus affect the cracking morphology in the coating. Therefore, based on the results of this study, if the coating and interfacial strengths are of similar magnitude with the substrate yield strength, the possible tendency of the substrate towards flow localization should be taken into account in the analysis of the coating behavior.

1. Introduction

The use of coatings offers a feasible means of controlling the surface properties of a component without notably affecting the underlying material. A natural question arising both in coating development and practical design work is the ability of the coating to properly function in the loading conditions imposed on the substrate material. That is, the coating has to be able to co-deform with the substrate without cracking or delamination. Often the coating material is considerably more brittle than the substrate and in most applications the surface is the most deforming region of a component due to bending loads. Therefore, the coating properties, such as ductility and interfacial strength, are critical design parameters.

An important point here is that the effective in-situ mechanical properties of a coating may depend on the underlying substrate material. For example, Kim and Nairn [1,2] reported notable differences in the effective fracture toughness of automotive polymeric coatings depending on the substrate material. The effect of the substrate material on coating behavior under normal loading, e.g., during hardness measurement or contact with a rigid sphere is frequently reported in the literature [3–5]. Moreover, Rehman et al. [6] noted that the measurement of the coating interfacial strength is affected by the plastic deformation of the substrate.

The background for this study comes from the notion that some substrate materials, such as certain low alloy steels, undergo intermittent strain softening and flow localization upon yielding [7]. That is, when the so-called upper yield point is reached during loading and plastic deformation begins, the flow stress of the material first decreases towards the so-called lower yield point and then increases again with continued plastic deformation. The consequence of this sequence of events is that the plastic deformation in the material localizes into a narrow band, the so-called Lüder's band, in which material deforms plastically at lower stress than the surrounding elastically loaded material. Depending on the state of loading on the solid body (uniaxial tensile/compression, bending etc.), one or more flow localization bands with varying orientation can emerge. Since these bands intersect the surface of the material, they can influence the behavior of the overlaying coating [8–11]. In fact,

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Nomenclature of the used symbols

β	linear strain rate sensitivity coefficient [MPa]
$\Delta\varepsilon_{app}$	apparent increase in the average surface strain [−]
ΔL_{sb}	horizontal displacement caused by the nucleation of shear bands [mm]
δ	coating thickness [mm]
ε^{el}_{ij}	elastic strain component *ij* [−]
ε_f	elastic normal strain at the moment of full damage (fracture) [−]
ε_p	equivalent plastic strain [−]
ε_{ps}	yield softening strain [−]
ε_{surf}	apparent surface strain during bending [−]
ε_{xsb}	average horizontal strain caused by shear bands [−]
ε_0	elastic normal strain corresponding to the initial fracture strength [−]
$\tilde{\varepsilon}$	maximum value of the principal strain during the damage process [−]
$\dot{\varepsilon}_p$	equivalent plastic strain rate [s^{-1}]
$\dot{\varepsilon}_{ref}$	reference strain rate [s^{-1}]
ν	Poisson's ratio of the material [−]
ρ_{crack}	crack density [mm^{-1}]
σ	coating failure strength [MPa]
σ_{f0}	initial fracture strength of the material [MPa]
σ_f	fracture strength of the material after damage [MPa]
σ_{ij}	stress component *ij* [MPa]
σ_I	maximum principle stress [MPa]
σ_{sr}	strain rate dependent component of material flow stress [MPa]
σ_Y	strain dependent component of material flow stress [MPa]
σ_{Yup}	upper yield strength [MPa]
σ_{Ylow}	lower yield strength [MPa]
τ	interfacial shear strength [MPa]
D	material damage [−]
E	Young's modulus of the material [MPa]
f	yield function
G_f	fracture energy [J/m]
h	height of the bending beam [mm]
K	linear strain hardening coefficient [MPa]
L	distance between the center supports in four point bending [mm]
L_c	distance between crack centers [mm]
L_0	characteristic element length [mm]
L_{0c}	saturated distance between crack centers [mm]
s_{ij}	deviatoric stress component *ij* [MPa]
w_{sb}	width of a region covered by shear bands [mm]
w	width of the bending beam [mm]

using the localized cracking of a brittle coating to detect Lüder's bands in the underlying metal is a relatively old technique [8]. Previous work [12, 13] also shows that in the case of a high strength coating the substrate shear bands and coating cracks interact; for example, substrate shear bands may cause the coating to fail locally and on the other hand, coating cracks can function as initiators of new localization bands.

The current study is motivated by the fact that even though the influence of substrate shear banding on the behavior of the overlaying coating has been reported in the literature, in general this phenomenon has received relatively little attention. Most of the measurements on coating properties are carried out on coatings overlaid on a substrate material (as opposed to so-called free-standing coatings). Given the large variety of different coatings and substrate materials, the measured coating properties should be as generally applicable as possible. Furthermore, the susceptibility of a material to yield softening and shear banding is affected by its microstructural state (such as solute atom content versus dislocation density) [7], which is dependent on the thermomechanical history of the material (prior plastic deformation, heat treatment etc.). Two nominally identical substrate materials may thus have different susceptibilities of flow localization and, in worst case scenario, notably different influence on the behavior of the overlaying coating. Based on these arguments, a systematic study on the effects of substrate shear banding on the behavior of thermally sprayed hard metal coatings is presented here.

The experimental results presented in this work are a part of a larger research project, which focuses on the characterization and further development of modern hard metal-coatings. In the current paper we study two coatings, that is, High Velocity Oxygen Fuel (HVOF) sprayed Cr_3C_2-25NiCr and a High Velocity Air Fuel (HVAF) sprayed WC-10Co4Cr coating on a S235 low alloy steel. The HVOF process can be considered to represent the current industrial standard process for producing high quality hard metal coatings, whereas the HVAF process is the latest step of development in hard metal spray technology [27]. Recently, experimental work has been devoted to the comparison of hard metal coatings sprayed with different HVOF and HVAF spray processes [28,29]. The coating/substrate-systems studied in the current paper were selected, because the substrate flow localization – induced effects are clearly evident in the experimental results. It is noted that the goal of this paper is not to evaluate the performance of the studied coating/substrate systems, but instead to draw generally applicable conclusions of the possible effects of substrate flow localization on the coating behavior.

A combined experimental-numerical work is carried out to characterize the prominent phenomena and to evaluate possible scenarios. In the experimental part we concentrate on three-point bending, since due to the geometry of the loading, the flow localization bands will form in a predictable fashion [14]. In situ digital image correlation (DIC) in sub-millimeter scale is used to experimentally characterize the interaction between the flow localization bands and different types of coatings. Then a continuum-based finite element method (FEM) model is constructed, compared with the experimental results, and then used to study the influence of different parameters, namely the coating and interfacial strength in relation to the substrate strength and the flow localization susceptibility.

2. Materials and methods

2.1. Thermal spraying of the coatings and resulting properties

The coated specimens were prepared by sand-blasting the surface of a 50 mm wide and 5 mm thick strip of S235 steel with mesh 36 Al_2O_3 grit and subsequently thermal spraying to obtain a coating thickness of approximately 0.2 mm. This target thickness was selected to obtain a reasonable compromise between practical relevance (thick enough to protect the substrate) and good coating quality (thin enough to avoid excessive formation of defects such as thermal strain induced cracks). As illustrated in Fig. 1, two different types of coatings are studied in this paper; a High Velocity Oxygen Fuel (HVOF: DJH2700, Oerlikon Metco, Switzerland) sprayed Cr_3C_2-25NiCr (Amperit 588.074, H.C. Starck, Germany) coating designated here as “HVOF CrC-NiCr” and a High Velocity Air Fuel (HVAF: M3, Uniquecoat Technologies LLC, USA) sprayed WC-10Co4Cr (Amperit 558.025, H.C. Starck, Germany) coating designated here as “HVAF WC-CoCr”. Particle velocities and temperatures during the coating process were measured with Spraywatch 4s online sensor (Oseir Ltd., Finland). The feedstock material and polished coating cross sections (Fig. 1) were characterized with scanning electron microscope (SEM: XL-30, Philips, Netherlands) and microhardness measurements were carried out with Vickers microhardness indenter (MMT-X7, Matsuzawa, Japan). Average hardness values were calculated from ten indentations done with 2.98 N force and 10 s load time.