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Microstructural design of self-lubricating laser claddings for use in high temperature sliding applications

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ABSTRACT

Nickel-based self-lubricating claddings with the addition of Ag and MoS_2 were prepared by means of laser cladding on stainless steel substrates, aiming at their implementation in metal forming applications involving demanding tribological conditions at high temperatures. The novelty of this approach is the addition of MoS_2 with the aim to achieve a uniform silver distribution within the resulting cladding by means of an encapsulation mechanism. This prevents it from floating to the surface during the deposition process and thus being subsequently lost during surface preparation. The role of Ag and MoS_2 concentration on the encapsulation process is discussed in terms of phase composition and resulting microstructures. The tribological behaviour of the resulting laser claddings was evaluated at up to 600 °C under unidirectional sliding. The encapsulation of Ag leads to outstanding tribological properties while keeping the concentration of used Ag low, thus increasing the economic viability of the claddings. An improvement in terms of both friction and wear was observed for the self-lubricating claddings compared to the nickel-based reference alloy, thus making them good candidates for use in high temperature applications such as hot metal forming.

1. Introduction

Metal forming processes performed at high temperatures (HT) are known to have significant advantages like the decrease of strain hardening and the increased ductility of the work piece material, which can reduce both the amount of energy required for forming and the scale of the machinery required for the process [1]. HT forming techniques include hot rolling, forging or hot stamping, the latter being of increasing importance in recent years for automotive applications [2]. However, from the tribological point of view, hot metal working involves demanding contact conditions which are responsible for the significant damage experienced by the tools during prolonged operation. In this context, reduced wear is not only beneficial in terms of maintenance costs [3], but it is also required to ensure the dimensional stability and the quality of the produced parts. As conventional lubricants degrade above 350 °C, new lubrication strategies at high temperatures need to be developed to mitigate tool wear and increase the overall efficiency of the hot metal forming process.

Solid lubricants in powder form have been considered as possible alternatives for HT applications, including metal forming, aerospace, power generation and even ore processing [4]. However, their use may also require an additional cleaning step to remove them from the surface of the finished parts or components [5,6]. This could be avoided by the development of multifunctional materials with self-lubricating behaviour at HT, an approach which is well referenced in the available literature for material classes such as PVD thin films, claddings and bulk materials [7–13].

The present study is focused on the deposition of HT self-lubricating coatings by means of laser cladding. This technique can be used for the deposition of protective thick layers which can decrease the wear experienced by metallic alloys and also can be used for the repair and refurbishment of key components such as expensive dies and tools in industrial applications [14–16]. The cladding process involves the use of a laser beam for the melting of a precursor material, generally used in powder form due to its large surface-to-volume ratio. The aforementioned powder can be either deposited on the surface to be coated (predeposition) or blown into the contact region (co-deposition). Different microstructures including hard phases in a ductile matrix can be achieved by changing process parameters [17], thus making it possible to obtain coatings with tailored mechanical and chemical properties. Some of the main advantages of laser cladding are summarised below:

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- The high quality of the resulting coating, as a low density of defects such as pores can be achieved [18].
- Reduced dilution with the substrate [19,20], potentially lower than 5%, due to fast solidification.
- Strong metallurgical bonding of the cladding to the substrate due to the aforementioned reduced dilution [21].
- The high efficiency of the process, as the laser beam can be accurately focused on the surface, thus decreasing energy consumption. Efficiency values as high as 50% can be thus reached [22].
- A microstructure with fine, metastable hard phases may be achieved, improving abrasion, corrosion and fatigue resistance among others.
- Reduced heat affected zone (HAZ) in the substrate material, due to controlled heat input [22,23].

Among the disadvantages, the following may be mentioned:

- High costs, both in infrastructure and training.
- High sensitivity to changes in process parameters [20].

The recently developed laser claddings generally excel in wear and corrosion protection at high temperatures but are not able to control friction. However, some attempts in developing laser claddings with self-lubricating properties for use at HT with the addition of solid lubricants like transition-metal dichalcogenides (TMDs) [24,25] and alkaline-earth fluorides [26], among others have also been made. Despite these attempts, the literature dealing with self-lubricating laser claddings is still limited, well behind other deposition techniques such as powder metallurgy or PVD. This might be related to the degradation of solid lubricants during deposition due to the high temperatures involved in the process.

Silver is in particular a well-known soft metal acting as a solid lubricant, having additional advantages for tribological applications like its high thermal conductivity. The combination of Ag and MoS_2 is particularly promising, as it has been reported to provide effective lubrication in a wide temperature range, potentially up to 800 °C, by means of the in-situ formation of lubricous silver molybdates at HT with an easy-to-shear microstructure due to the weak Ag–O bonding [27]. Additionally, the sulfur contained in TMDs is considered to be beneficial as it can decrease the diffusion rates of silver at HT. Thus, the addition of TMDs like MoS_2 to self-lubricating materials is expected to slow silver depletion and extend their lifetime without the need for diffusion barriers like the ones used in PVD coatings [28–30].

Taking into account the previous work, silver and molybdenum disulfide have been chosen in the present study for incorporation to nickel-based, self-lubricating laser claddings. The microstructure of the resulting claddings and their tribological behaviour at HT were investigated as a first step towards their potential use in metal forming applications as wear and friction controlling coatings.

2. Experimental

2.1. Materials preparation

A direct diode laser with a wavelength of 975 nm was chosen for the deposition of the self-lubricating claddings, as this technique allows for a single-pass melting of the precursor material avoiding the re-melting of the resulting claddings. A NiCrSiB commercial powder supplied by Castolin Eutectic was chosen as the base material of the cladding alloy, with a chemical composition consisting of 0.2 C, 4 Cr, 1 B, 2.5 Si, < 2 Fe, 1 Al and balance Ni (in wt%) and a particle size between 50 and 150 µm. Boron and silicon additions lower the melting point of the cladding powder, which is beneficial for the deposition of this nickel-based self-fluxing alloy [31]. Ag powders to be used as solid lubricants were procured from Goodfellow, with a maximum particle size of 45 µm. MoS_2 was provided by Tribotecc GmbH, with a particle size between 5 and 75 µm. The base powder and the solid lubricants were mechanically mixed using ethanol as binder, and spread over a 1.4301 grade stainless steel plate. The substrate alloy was chosen to prevent oxidation during subsequent HT tribotesting. Prior to the deposition, a sandblasting step with silica sand was performed in order to improve the adhesion of the resulting claddings. Afterwards, a heating step was performed in an oven at 100 °C for 1 h, to ensure the evaporation of the ethanol binder. The final step of laser cladding was performed using a rectangular shaped beam of 24 × 3 mm^2 with a protective argon atmosphere to prevent the oxidation of the resulting coatings. The cladding samples used in the present study were prepared using beam speeds between 7.5 and 11.0 mm/s and beam power inputs from 4700 to 7000 W depending on the sample geometry and dimensions, and were subsequently ground after preparation.

Table 1
Solid lubricant content for the deposited coatings.

Claddings	Solid lubricant content (wt%)		RT hardness [HV1]
	Ag	MoS_2	
Reference	0	0	356 ± 11
10 MoS_2	0	10	409 ± 6
3 Ag–10 MoS_2	3	10	399 ± 16
5 Ag–10 MoS_2	5	10	386 ± 37
10 Ag–10 MoS_2	10	10	395 ± 13
15 Ag–10 MoS_2	15	10	393 ± 4
10 Ag–15 MoS_2	10	15	407 ± 10

The chemical compositions of the precursor powders mixtures used for the laser claddings are listed in detail in Table 1. An unmodified NiCrSiB alloy was used as the reference material, in addition to several self-lubricating claddings featuring different silver and MoS_2 contents. This was aimed at studying the role of different concentrations of both compounds in the resulting microstructure, hardness and HT tribological behaviour of the coatings.

2.2. Hot hardness measurements

Hardness at high temperatures is an important parameter in tribological applications as it has been shown to correlate with both the yield strength and wear resistance of metallic alloys [32]. In the present work, the hot hardness of the most relevant as-deposited laser claddings measured using a test rig developed at the Austrian Center of Competence for Tribology (AC2T research GmbH) described earlier in [33]. The following claddings were chosen for hot hardness measurements: the unmodified base alloy used as the reference, the self-lubricating cladding 5 Ag–10 MoS_2 which was considered to be optimum in terms of microstructure as it will be further detailed, and its silver-free counterpart 10 MoS_2.

Vickers indentation tests (HV10) were performed at RT, 150, 300, 400, 500 and 600 °C. The testing chamber was kept under low vacuum conditions (5 mbar) to prevent damage to the diamond indenter by oxidation. Three indentations were made for each temperature, and the hot hardness measurements up to 600 °C were performed on two different samples for each material, to ensure the repeatability of the results.

2.3. High temperature unidirectional sliding tests

For the tribological experiments, the reference alloy, 5 Ag–10 MoS_2 in addition to 10 MoS_2 were deposited in a single pass laser cladding step on ring-shaped samples with an external diameter of 90 mm and tested under unidirectional sliding motion against three equi-spaced cylindrical flat pins (Ø4 × 12 mm) made of AISI 52100 bearing steel, which were used as the counter bodies. The ground and rounded edges of test pins were expected to reduce the indentation (edge) effect when