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# Effect of the remelting scanning speed on the amorphous forming ability of Ni-based alloy using laser cladding plus a laser remelting process

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ABSTRACT

Amorphous coatings exhibit prominent properties, including high hardness and good wear resistance properties. In this study, Ni-based amorphous composite coatings with a composition of $(Ni_{0.6}Fe_{0.4})_{68}B_{18}Si_{10}Nb_4$ were prepared on a mild steel substrate via high power diode laser cladding plus laser remelting processes. The microstructure of the coating was studied using X-ray diffraction (XRD) and a scanning electron microscope (SEM). The effect of the remelting scanning speed on the amorphous forming ability of the Ni-based alloy was studied systematically by experimental and numerical simulation methods. The results indicated that there was no amorphous phase formed when the scanning speed was 4 m/min and 5 m/min. The amorphous phase was observed when the remelting scanning speed was 6 m/min. The amorphous phase volume fraction increased with an increase in the remelting scanning speed. The fraction was found to be approximately 64% when the remelting speed was 8 m/min. The simulation results indicate that the increase in the remelting scanning speed may lead to lower residence time and higher cooling rate of the melted pool. As a result, high remelting scanning speed can be concluded to be a necessary condition for the formation of the amorphous phase when using the laser cladding plus laser remelting process.



## 1. Introduction

Recently, amorphous alloys have attracted an increasing amount of attention due to their unique physical, mechanical and chemical properties [1]. In most cases, the amorphous alloys were prepared in the form of ribbons, powders and wires of small thickness or diameter. Therefore, the application of amorphous alloys as a structural material has been limited [2,3]. Recently, it has been reported that many amorphous coatings of Zr-based, Cu-based, Fe-based and Ni-based alloys were successfully coated onto metallic components and that these coatings exhibit optimised mechanical properties compared to the properties of the crystalline substrates [4–7].

Rapid cooling is the main consideration for the selection of metallic glass synthesis techniques [8,9]. A laser, as a source of coherent and monochromatic radiation and a directed source of non-contact heating, offers a wide scope of applications in the surface engineering of ferrous and non-ferrous materials [10,11]. The cooling rate in the laser remelted process with a fast scanning speed can achieve $10^5$–$10^8$ K/s, which is much higher than the critical cooling rates of bulk metallic glasses (BMGs), which makes it possible to synthesise metallic glass through laser melting or powder cladding onto the crystalline substrate [12]. Zhang deposited the PEEK (poly-ether-ether-ketone) coatings using the combined flame spraying-laser remelting process. The results indicated that both the PEEK powder and the as-sprayed coating exhibit a semi-crystalline structure. The laser-treated coatings, however, exhibit an amorphous structure [13]. Cui studied the microstructure and corrosion resistance properties of Fe-based alloy coatings deposited by the High Velocity Oxy-Fuel (HVOF) technique. Some amorphous phases were found in the as-sprayed coatings after laser remelting [14]. Ye synthesised a crack-free Fe-Cr-Mo-W-Mn-C-Si-B metallic glass composites with a large fraction of amorphous structure by laser remelting in the overlapping region during the multi-track laser cladding process [15]. Using two-step laser cladding followed by a laser remelting process, Matthews synthesised a Cu-based metallic glass coating on a Ti substrate, and the tribological properties were analysed by sliding wear tribotesting [5]. Zhang [16] and Li [17] also used the processes of two-step laser cladding followed by laser remelting in producing Fe-based and Ni-based amorphous composite coatings, respectively. However, among these studies, the influence of the remelting scanning speed on the structure of the remelted coatings and the mechanisms of influence are seldom studied.

In this paper, the microstructures of laser remelted Ni-based coatings are observed, and the amorphous volume fractions at different

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remelting scanning speed are calculated. The mechanisms of influence of the remelting scanning speed on the amorphous forming ability are systematically studied by FEM simulation.

## 2. Experimental procedure

Elemental powder blends with nominal compositions of $(Ni_{0.6}Fe_{0.4})_{68}B_{18}Si_{10}Nb_4$ (in at.%) were chosen as the cladding materials due to their known glass forming ability in rapid solidification and the results of our previous studies [18–20]. Substrates of dimensions of 8 mm × 20 mm × 120 mm were cut from the mild steel sheet in annealed condition and polished before laser treatment.

The laser radiation was provided by a Rofin high power diode laser (HPDL, model DL035Q), which delivers a maximum output power of 3.5 kW in continuous wave mode at wavelengths of 808 nm & 940 nm. The powder was fed by a COAX-8 continuous coaxial nozzle, developed by the Fraunhofer IWS Institute. The laser beam was focused by means of a lens onto a spot with size of 3.3 mm × 2 mm at the substrate surface. The laser process was divided into two sections of laser cladding plus laser remelting. First, for the laser cladding process, the laser power was 0.8 kW, the scanning speed was 360 mm/min and the powder feeding rate was 12 g/min. Second, the scanning speed ranged between 4 m/min to 8 m/min, and the laser power was 3.5 kW. All experiments were conducted under an inert argon atmosphere.

The microstructures of the coatings were examined using a JSM 6460 scanning electron microscope (SEM). The phase composition of the laser remelted coating was observed by X-ray diffraction using a D/max2550VL/PC apparatus equipped with a Cu-Kα radiation source. Digital metallic Vickers hardness tester (HVS-10) was used to measure the microhardness of the coatings. The microhardness along the cross profile of the coatings was measured by using a Viker's microhardness tester (HVS-10) with a load of 0.5 kg.

## 3. Results and discussions

Fig. 1 shows the cross-sectional macro image of the coating produced by the laser cladding plus laser remelting process when the laser scanning speed was 8 m/min. The coating is found to be separated into two layers, as indicated by the dotted line shown in Fig. 1. The depth of the remelted layer is approximately 250 μm. The colour contrast in the remelted layer is almost the same, which indicates the structure is almost uniform. In this paper, the laser cladding parameters were kept uniform with low linear heat input. Then, the dilution effect of the substrate almost has no influence on the chemical composition of the coating, especially in the remelted layer [20]. So the influence of chemical composition on the amorphous forming ability of the coating can be ignored. The remelted depths at other scanning speed from 4 m/min to 9 m/min were also measured and depicted in Fig. 2. Fig. 2 shows an inverse ratio between the remelting depth and the scanning speed. The remelting depth decreases with the increase of the scanning speed. The speed of the moving laser beam is related to the action

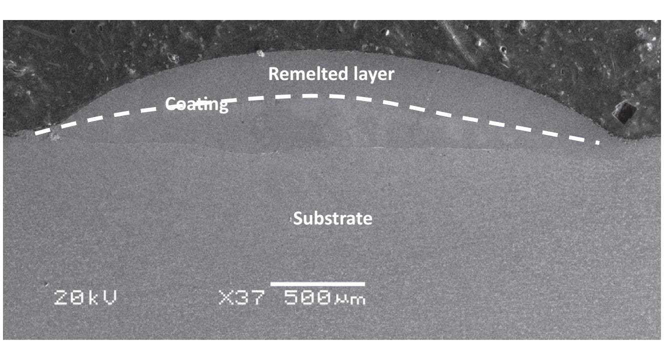


**Fig. 1.** Interfacial macro SEM images of the laser cladded coating after laser remelting for the laser remelting scanning speed of 8 m/min.

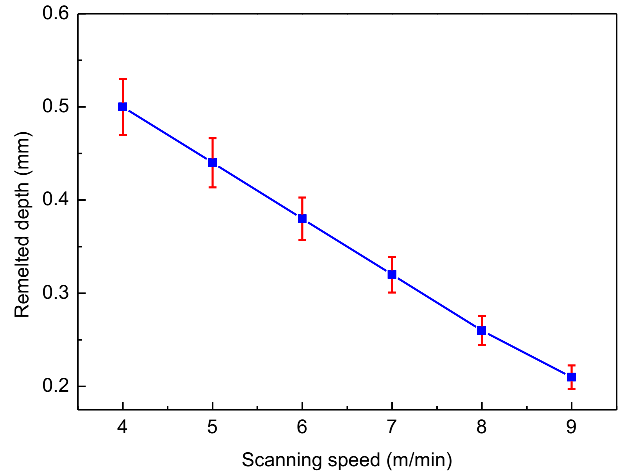


**Fig. 2.** Remelted depth versus scanning speed after the laser remelting process.

time between the laser beam and the cladded coating and affects the heating input of the laser. Under a slow scanning speed, the action time between the laser beam and the cladded coating is longer. Much more heat was introduced into the coating. The remelted depth in the coating was greater. When the laser scanning speed is higher, the remelted depth became shallower.

Fig. 3 shows the interfacial microstructure of the remelted layer at different scanning speeds. The microstructure mainly consists of coarse dendrites at 4 m/min. At 5 m/min, the dendrites became finer. When the remelting scanning speed is 6 m/min, no region of crystal characteristics can be seen in the remelted layer, i.e., it is mainly in the amorphous phase. The confirmation of the amorphous phase using TEM imaging could be seen in my previous study [17]. Therefore, both dendrites and the amorphous phase are formed in the remelted layer, while the fraction of dendrites is larger than that of the amorphous phase. For a scanning speed of 7 m/min, the fraction of the amorphous phase increases further, with the fraction of the amorphous phase being greater than 50%; in other words, the amorphous phase is much greater than that of the dendrites phase. At scanning speeds of 8 m/min and 9 m/min, the fraction of the amorphous phase becomes increasingly large. The amorphous phase is the primary phase in the remelted layer.

Fig. 4 shows the XRD patterns of the laser remelted layer at different laser remelting scanning speeds. Fig. 4 shows that only sharp crystalline peaks were observed for samples processed at scanning speeds of 4 m/min and 5 m/min. This result indicates that only crystalline phases are formed under the slower scanning speeds. In addition, the crystal phases are γ(Fe, Ni) phase and NbC phase. When the laser remelting scanning speed ranges from 6 m/min to 9 m/min, the XRD patterns exhibit broad halo peaks at the diffraction angle of 44° (2θ); the diffraction peaks correspond to some crystalline phases, implying partly amorphous phase layers are obtained. The amorphous phase fractions of the remelted layers were calculated by the Verdon method [21], as presented in Table 1. The data in Table 1 indicates that the fraction of amorphous phase increases with increase in the laser remelting scanning speed.

Fig. 5 shows the measured microhardness for the obtained laser cladding plus remelting coatings along the cross-section from the substrate to the remelted layer. The microhardness of the cladded layer and the remelted layer are all much higher than that of the mild steel substrate; and the highest hardness occurs in the remelted layer. This behaviour is attributed to the formation of the amorphous phase and the fine microstructure within it. The microhardness of the coating was found to increase with the increase in laser remelting scanning speed, as does the volume fraction of the amorphous phase. For the remelting speed of 8 m/min and 9 m/min, the remelted layer has an extremely high hardness of 1210.4 $HV_{0.5}$ and 1209.5 $HV_{0.5}$, respectively,