Effects of lateral and vertical ultrasonic vibrations on the microstructure and microhardness of Stellite-6 coating deposited on Inconel 718 superalloy through laser metal deposition

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Keywords: laser metal deposition, Nd:YAG, Inconel 718, Stellite-6, microstructure

Abstract
In this research work, Stellite-6 was deposited on an Inconel 718 substrate via laser metal deposition (LMD) process. Lateral and vertical ultrasonic vibrations were applied during the LMD process at 150 W and 250 W to achieve improved properties. The resultant coatings were evaluated by scanning electron microscopy (SEM) equipped with an energy dispersive spectroscopy (EDS) analyzer and optical microscopy. Also, the microhardness values of two samples (without vibration and with vertical vibration) were measured. The results showed that applying ultrasonic vertical vibrations led to significant changes in the microstructure of the coatings and the coating/substrate interface i.e. a better distribution of alloying elements of the coating was achieved, the number of the secondary arms increased, and the porosity percentage decreased significantly. Moreover, the microhardness value in the sample synthesized at 150 W and under vertical vibrations were higher than that in the sample produced without vibrations.

1. Introduction
Inconel 718 (IN 718) is a Ni-base, precipitation hardenable alloy with unique properties including high yield, tensile strength, creep-rupture properties [1] and excellent impact strength, fracture toughness at low temperatures, and corrosion resistance [2]. Owing to these properties, IN 718 is widely used in aviation and aerospace industries as well as gas turbine engines and cryogenic tankage. However, this alloy is mostly employed at temperatures ranging from −250 °C to 750 °C and its performance is limited at temperatures higher than 750 °C owing to decreased toughness and wear properties caused by the formation of carbides and intermetallic compounds as a result of the Nb segregation [2, 3]. The wear mechanisms including lamination occur in this superalloy due to the accumulation of dislocations behind the obstacles and the force applied by these accumulated dislocations cause plastic deformation and microscopic pores [4]. By applying higher forces, the size of these pores increases and the coalescence of these pores leads to the formations of cracks [5]. Therefore, the surface properties can be improved by applying a thin layer of appropriate materials such as Stellites which are cobalt-based superalloys that retain their hardness at high temperatures and/or corrosive, abrasive environments [6–8].

Wear-resistant Stellite coatings are applied by various methods such as thermal spraying [9], gas tungsten arc welding (GTAW) [10], plasma transferred arc (PTA) [11], flame spraying [12], and laser metal deposition (LMD) [13]. LMD is a laser cladding approach which can be used to fabricate functional, three-dimensional components. During LMD, a melt pool on the substrate surface or a previous layer is generated by the radiation of a high-power laser beam. Concurrently, metal powders are injected into the melt pool by a feeding nozzle and are entirely melted. By moving the working table and/or the laser head, a metallurgical fused bonding is formed. There are several advantages to using LMD. For example, highly complex parts can be repaired via an automated method and, since the heat input is low, the heat affected zone is somehow negligible. Therefore, not only the
strength of material is not suppressed but also the distortion is also remarkably lower than conventional techniques. Nonetheless, there may be some restrictions with the application of this method. For instance, anisotropy in the mechanical properties occurs owing to the layered microstructure and residual stresses that are commonly present because of steep thermal gradients [14]. In addition, the formation of defects such as porosity requires the use of modified LMD techniques or using auxiliary tools to improve the final characteristics.

One of the auxiliary methods to improve the quality of products in casting and welding processes is the employment of vibrations. It has been reported that mechanical vibration can modify the microstructure of the components and restrain the defects [15]. Also, the literature review reveals that it can reduce the shrinkage cavity defects [16] and enhance the fatigue properties and the impact resistance of the as-cast components [17]. Froozmehr et al [18] investigated the effect of vibrations on the laser powder deposition process. They reported that the porosity percentage decreased by about 60% in parallel vibrations and about 80% in lateral vibrations. Moreover, under vibration, the length of dendrite arms decreased. Nazir et al [19] employed a vibration control feeding system in the direct laser deposition process to increase the quality of the produced coating layer. Fouladi et al [20] applied vibration during the friction stir welding method and concluded that the employment of vibration led to the reduction of grain size in the welded zone. In addition, the strength and ductility of the as-vibrated specimens were higher than the non-vibrated specimens while the corrosion resistance in the vibrated specimens was degraded. Liu et al [21] investigated the effect of ultrasonic vibrations on the friction stir welding process of AZ31 magnesium alloy and deduced that the force and the torque of the tool required to perform the process could be majorly reduced by applying vibrations.

Therefore, to the best of the authors’ knowledge, the application of ultrasonic vibrations is beneficial to the characteristics of coatings obtained by the LMD process. However, the literature is scarce on the use of vibrations in this process. In previous papers, electromagnetic vibrators with a frequency of 1000 Hz to apply vibrations to workpieces were used. Electromagnetic vibrators are expensive and are also difficult to install to the laser working table. However, in this study, a magnetic generator with the capacity of generating and transferring ultrasonic vibrations with the frequencies up to 20 kHz was manufactured by the authors which is cheap and easy to install on the laser working table. Moreover, the waves applied in this research was totally different i.e. the frequency generated by the oscillator was 17 kHz. The waves were completely ultrasonic while the waves in the previous studies were mechanical or a combination of mechanical and ultrasonic waves. Motivated by this background, in this study the effects of vertical/lateral ultrasonic vibrations during the LMD process on the microstructure and mechanical properties of the Stellite-6 coating on Inconel 718 will be scrutinized in details.

2. Experimental procedure

Plates of Inconel 718 with a thickness of 1 mm were used as substrates for the laser metal deposition process. Table 1 shows the chemical composition of Inconel 718 provided by the Special Metals Corporation company. The density of this material is 8.19 g cm$^{-3}$ and its melting point is in the range of 1260 °C–1336 °C. It should be mentioned that in addition to the elements presented, minor concentrations of Mn, Si, F, and Cu are present in the chemical composition of IN718.
Powders of Stellite-6 were used as the coating material to synthesize a coating on the IN718 substrate. The chemical composition of Stellite-6 powder is also displayed in Table 1. The Stellite-6 powder is a product of Deloro Stellite company with a particle size range of 38–106 μm, a density of 8.44 g cm⁻³, and the melting point in the range of 1285 °C–1410 °C. Along with the elements mentioned in Table 1, minor amounts of other elements including Mn, Mo, Si, and N were present in the composition of Stellite-6.

An Nd:YAG pulsed laser machine (IQL-10) with a nominal power of 400 W was used for the powder cladding process. The output pulses of the laser were squared and the distribution of the laser beam energy in all the samples was Gaussian (the Transverse Electromagnetic Mode). A laser power sensor (A-500W-Lp Ophir) was employed in the experiments to measure the average power.

The laser metal deposition process was performed through the use of a powder injection machine by a twin powder feeder. This gravity-based powder feeder consists of a rotating disc wheel and a tank, and the desired powder flows into a groove on the rotating disk due to gravity and gas pressure and the powders are transferred to the suction unit by the gas flow. It is clear that the groove dimensions and disk speed (rpm) simply control the volume of the feeding powder.

![Figure 1. The schematic and (b) the actual image of the system used in this research for the LMD process.](image)

**Table 3.** The porosity percentage of the laser-deposited coatings in samples 1, 3, and 5.

| Sample code | 1   | 3   | 5   |
|-------------|-----|-----|-----|
| Type of vibration | Lateral | Vertical | No vibration |
| Porosity percentage | 0.16 | 0.1 | 0.32 |
It should also be mentioned that high purity argon gas was used both as a carrier gas for the powders and as a shielding gas at all stages of the experiments. During the process, argon gas was purging to the surface to protect the melt pool from the atmosphere. Furthermore, it facilitated the transfer of the considered powder to the substrate surface.

Table 2 predicts the characteristics of the laser power employed and the vibration type for the samples produced. It should be noted that the laser scanning speed and the powder feeding rate for all the samples were $3 \text{ mm s}^{-1}$ and $0.4 \text{ g s}^{-1}$, respectively.

The schematic of the system and the actual image of the system used for the laser metal deposition process used in this research can be found in figure 1. It is noteworthy that in samples 1 to 4, the frequency of the vibrating waves was 17000 Hz. In the vertical waves, the phase difference was $180^\circ$ while in the lateral ones, it was $0^\circ$. Also, it should be mentioned that the instrument does not show the amplitude.

To study about the microstructure of products, the samples were cut to prepare their cross-sections followed by cold mounting. The mounted samples were ground using 80, 240, 320, 600, 1200, and 2400 grinding papers. Then the samples were polished by a polishing cloth and a diamond paste ($1.4 \mu\text{m}$). Electroetching was carried out on the samples at 6 V for 1 min. The solutions used for electroetching the coating layer included Oxalic acid (10%) while it comprised of 60 cc alcohol, 35 cc glycerin, 10 cc lactic acid, 5 cc phosphoric acid, and 2 cc citric acid for electroetching the substrate. Then, the microstructures of the samples were investigated using an optical

**Figure 2.** The OM micrographs of (a) sample 1, (b) sample 3, and (c) sample 5.

**Table 4.** The porosity percentage of the laser-deposited coatings in samples 2, 4, and 6.

| Sample code | 2     | 4     | 6     |
|-------------|-------|-------|-------|
| Type of vibration | Lateral | Vertical | No vibration |
| Porosity percentage | 0.07  | 0.04  | 0.1   |
microscope (BH2-UMA/ Olympus, Japan). Moreover, the geometry and the porosity percentage of the microstructure were evaluated by Digimizer and Image Tool software programs, respectively. To study the microstructures, a scanning electron microscope (SEM-XL30, Philips, Netherlands) equipped with an energy dispersive spectroscopy (EDS) analyzer was employed. In order to measure the hardness variations of the laser cladded coatings, a microhardness tester (MATSUZAWA-MHT2 model, Japan) was used. The measurements were carried out according to the ASTM E9 standard as a hardness profile along the longitudinal direction of the samples (from the as-cladded coating to the substrate). A force of 100 g and a dwell time of 15 s were applied to conduct the hardness measurements.

3. Results and discussion

3.1. Optical microscope observations

At low power values, the G/R ratio is low and the most common defects can be seen in the coatings. It should be noted that G is the thermal gradient and R is the solidification rate. On the other hand, the G/R ratio is not the same in different regions of the laser deposited layers. Therefore, the selection of the parameters mentioned for this stage of the research was completely intentional in order to observe the different effects of vibration on the laser-deposited layers. According to the statements presented in [22], the equiaxed growth of dendrites and common defects occur at low G/R ratios while the columnar growth of dendrites takes place at high G/R ratios.

Figure 2 presents the optical micrographs of the laser-deposited coatings in samples 1, 3, and 5. This figure interestingly proves the effect of vibrations on the geometry of the laser-deposited coatings. It can be found that the width and the height of the coatings were affected by the vibrations. Table 3 displays the porosity percentage of the laser-deposited coatings in samples 1, 3, and 5. According to these results, it can be deduced that the ultrasonic vibrations applied to the samples decreased the porosity percentage in the laser-deposited coatings.
i.e. the porosity percentage in sample 5 (without vibration) was 0.32 while it decreased to 0.1 and 0.16 under the use of lateral vibrations and vertical vibrations, respectively. Thus, the employment of lateral ultrasonic vibrations gave rise to significant reduction of porosities than that of vertical waves.

Figure 3 shows the optical micrographs of samples 2, 4, and 6. In fact, these micrographs depict the microstructures of the coatings obtained at 250 W. It can be found that at higher powers, the porosity percentages of the as-coated layers during the solidification process was surprisingly lower than those deposited at lower powers. Moreover, the dimensions of the layers deposited by the LMD process at higher powers were much higher than those deposited at lower powers. This means that at higher powers, higher amounts of coating can be obtained that is in a good agreement with the use of higher heat inputs. In addition, the dendritic regions were observed in the laser-metal deposited coating under different condition in figure 4. Under vibration, the length of the dendrite arms decreased but the width of the arms increased slightly. Also, the number of the secondary arms in both directions of ultrasonic vibrations increased which was more pronounced in the structure of the coating structure deposited under vertical vibrations.

Table 4 displays the porosity percentage of the laser-deposited coatings in samples 2, 4, and 6. Similar to the results of the samples 1, 3, and 5, the porosity percentage in these samples decreased significantly through the employment of lateral and vertical ultrasonic vibrations. Therefore, it can be deduced that applying vibrations can overcome the problem of the formation of porosities in the laser metal deposited coatings to a great extent. The reason is that vibrations applied energy to the melt through agitation and increased convection velocity. Therefore, the gas and lightweight inclusions, which result in the formation of porosities, float toward the coating surface.
Also, vertical vibrations were more effective than lateral vibrations to reduce the porosity percentage as well as to decrease the maximum size of porosities. This can be ascribed to the fact that vertical vibrations were applied along the gravity direction. In fact, vertical vibrations and gravity exhibited a synergistic effect i.e. increased the pore filling capability which led to the reduction of porosities.

### 3.2. SEM investigations

Figure 5 shows the SEM images of samples 1, 3 and 5. Figures 5(a) and (b) show the microstructure of the sample coated with Stellite-6 without vibration at different magnifications. According to the regions marked by 1 and 2 in Figure 5, the difference between the microstructures of the as–coated region and the base metal is clearly evident. In fact, the structure of the coating is coarse dendritic. Figures 5(c) and (d) show the microstructure of sample 3 which underwent lateral vibrations. By comparing Figure 5(b) with Figure 5(d), it can be observed that the microstructure became finer and more similar to equiaxed microstructures. Noteworthy, the color difference between the substrate and the coating in samples 3 and 5 disappeared. This indicates that with
applying vibrations, the coatings became more similar to the substrate which is considered an advantage for the process used in this study.

Moreover, by comparing Figure 5(d) with Figure 5(f), it can be found that with applying vertical vibrations, a finer microstructure could be obtained with a much lower amounts of porosities in the coating/substrate interface.

Figure 6 shows the SEM images of samples 2, 4, and 6 deposited at 250 W. These images show that increasing the laser power from 150 W to 250 W gave rise to the reduction of cavities and porosities while the uniformity of the coating surface was significantly enhanced. The reason can be related to the fact that at high powers, the G/R ratio was high and the appearance of coating defects at high G/R ratio was less probable. Furthermore, the dendritic structure became coarser.
The mechanism of the refinement of dendrites under the application of ultrasonic vibrations in brief is that the nucleation region extends to a larger area or even to the whole molten metal. During solidification, the growing dendrites will break off and turn into new nucleation sites. This means that the growth of dendrites will be limited and the microstructure is refined. According to our results, it seems that the coatings synthesized without ultrasonic vibrations exhibited the worst quality while the coating deposited using vertical vibrations at 150 W exhibited the highest quality among the samples. In addition, the energy of ultrasonic vibration appeared to have the potential to break off the dendrite arms by stirring the fluid during solidification. Moreover, a slight increase in the grain width as well as an increase in the number of secondary dendrites may be due to a decrease in the thermal gradient from the melting line toward the section center. Fractured dendrite fragments moved toward the pool center with the fluid flow and grew as new nuclei along the main growth path but some grains might be randomly formed.

In general, another mode of nucleation is dynamic nucleation, in which, vibrations create tension in the melt and vibrate the melt. Vibrations can refine the microstructure in two following ways: 1- The cavitation phenomenon: Vibrations cause applying tensile forces on the molten layers, resulting in the formation of cavities in the molten layers. But followed by tensile forces, compressive forces are also applied on the molten layers causing the explosion of bubbles. According to the Clasius-Clapeyron equation, increasing the pressure applied on the molten layers increases the melting point of the alloy, and consequently according to the solidification rules, the critical radius of the grain decreases. This means that nucleation becomes much easier. 2- Crystal multiplication: After increasing the dendrite root concentration under constitutional undercooling, the dendrite branches are broken off by applying ultrasonic vibrations and serve as nuclei for the crystal multiplication. In other words, the fractured branch is of the melt type, meaning higher wettability and a wetting angle of 0° which is no longer a barrier to nucleation or growth. Crystal multiplication accelerates
non-homogenous nucleation because external factors are involved and its condition is the presence of a significant percentage of the solid phase (dendrites) [23].

Figures 7–9 present the EDS-map elemental analysis results related to samples 1, 3, and 5, respectively. It can be found that although there was no significant difference between the concentration of Nb in these samples, the wt. % of Nb distributed in the matrix in sample 3 was higher than that in sample 1 while in sample 5 (no vibration applied) the concentration of Nb was higher than that in samples 1 and 3. This can prove that the distribution of Nb in the no-vibration condition was poorer and segregation may be an issue in this sample as mentioned in the literature [2, 3]. Moreover, the uniform distribution of the other elements in samples 1 and 3 demonstrates that ultrasonic vibrations could significantly inhibit the segregation of the alloying elements during solidification.

3.3. Microhardness measurements
Figure 10 shows the microhardness profiles obtained from two samples of 3 and 5. It is observed that sample 3 (vertical vibrations) exhibited higher microhardness values in the interface and the regions around it. This phenomenon can be explained by the effect of vibrations to decrease the grain size in dendritic regions as well as increasing the area of grain boundaries. As a result, dendritic regions under vibrations exhibited higher hardness values than those under non-vibrational conditions. In addition, vibrational conditions in the LMD process increased the size of the equiaxed grains in the pool center, and the overall result was that the uniformity of the hardness throughout the coating increased with the application of vertical vibrations.
4. Conclusions

Stellite-6 was successfully deposited on an Inconel 718 substrate by LMD process. Moreover, vertical/lateral ultrasonic vibrations were employed during the LMD process. The most important conclusions of the present research include:

- Porosity was significantly reduced by applying ultrasonic vibrations. Vertical vibrations were more effective than lateral ones.
- More uniform coatings were achieved through the employment of vibrations.
- With applying vertical vibrations, a finer structure was obtained with a much lower amount of porosities in the coating/substrate interface.

Figure 9. The EDS-map elemental analysis of sample 5.

Figure 10. The microhardness values of samples 3 and 5.
- Ultrasonic vibrations could significantly inhibit the segregation of the alloying elements during solidification.
- Vertical ultrasonic vibrations led to higher microhardness values in the interface.

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