Effects of substrate preheating on the thin-wall part built by laser metal deposition shaping

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\begin{abstract}
Laser metal deposition shaping (LMDS) is a state-of-the-art technology that combines rapid prototyping and laser processing. There are many factors affecting the quality, precision, microstructure and performance of the LMDS-deposited parts. Among these factors, substrate preheating is a significant one because it can change the heat history of the LMDS process. Preheating is generally adopted to reduce the residual stresses and the risk of thermal distortion and cracking. However, it changes the heat transfer conditions and affects the final microstructure and properties. In this work, a numerical simulation model was established to analyze the heat transfer characteristics between deposited material and substrate, the influence rules of substrate preheating on the thermal behavior during LMDS, and the distribution characters of temperature and stress field. And then, the experimental methods were used to evaluate the effects of substrate preheating on the surface quality, microstructure, composition, hardness distribution, and mechanical properties of as-built thin-wall parts. The experimental results primarily agree with the theoretical analysis and numerical model, which indicates that in terms of the varied thermo-mechanical coupled field, the investigated microstructure and properties of formed components depend considerably on the initial temperature of the substrate, so the LMDS process can be effectively adjusted and controlled by means of substrate preheating.
\end{abstract}

\section{Introduction}

Laser metal deposition shaping (LMDS) has been developing for a few years for rapid manufacturing\,\cite{1–6} and rapid tooling\,\cite{7–10} applications. During the process, the parts are built by overlapping consecutive layers of the laser melted material on the prepared substrate. Since cooling involves heat conduction to the bulk, the material in each layer will undergo successive thermal cycles as new layers are deposited. Such short duration thermal cycles can induce solid-state transformations in the previously deposited layers, and lead to progressive modification of their microstructure and properties. In the process of LMDS, the thermal history will differ from point to point in the part, depending on the processing parameters, scanning pattern, build-up strategy, substrate preheating temperature and geometry of the part being built. As a result, the type and extent of the solid-state phase transformations induced by the thermal field in the part may vary from point to point, thus leading to the complex distribution of microstructure and properties observed experimentally\,\cite{11}.

With the features of collective energy input and rapid heating and cooling, the LMDS process can induce considerable temperature gradient and thermal stress between as-formed part and substrate. As the thermal stress exceeds the material strength, cracks and ruptures will appear in the parts. Accordingly, modifying the temperature distribution during the process, reducing the substantial temperature gradient and thermal stress, and restricting the crack/distortion caused by deposition shaping have become the important and urgent issues to LMDS process. Among the factors influencing the thermal history, substrate preheating is an effective one to resolve the above-mentioned issues, because it can improve the adhesion and heat transport for the initial deposited powder, and significantly reduce the temperature gradient between part and substrate by homogenizing the temperature field.

In order to prove the significance of substrate preheating, Costa et al.\,\cite{11} proposed a model describing the complex structural transformations during the deposition process to predict the final microstructure and properties of the laser powder deposited part and evaluate the effects of substrate preheating on the final process.
Table 1
Chemical compositions of powder and substrate (wt.%).

<table>
<thead>
<tr>
<th>Material</th>
<th>Chemical composition (wt.%)</th>
</tr>
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<tbody>
<tr>
<td>Ni60A</td>
<td>C  1.0  B 3.5  Si 4.0  Fe 17  Ni 5.0  S 0.024  P 0.021  Mn 0.48</td>
</tr>
<tr>
<td>Q235</td>
<td>C 0.16  B 0.22  Si  Bal.</td>
</tr>
</tbody>
</table>

hardness distribution. However, more comprehensive effects combined with experiments have not been stated; Shishkovsky with co-authors [12] reported that Selective Laser Melting (SLM) with additional heating up to 500 °C gave much more promising results by the layerwise remelting of the NiTi intermetallic phase. They performed the related tests and analyses to the 3D SLM rectangular samples fabricated with preheating temperature of 500 °C, but not concentrated on the effects of varied preheating temperatures on the samples; Fallah et al. [13] studied the impact of localized surface preheating on the microstructure and crack formation in laser direct deposited sample, but their the conclusions neglected the influence rules of different preheating temperatures. Chao et al. [14] address the appropriate combination of droplet and substrate temperatures through the related numerical model and deposition experiments, so they can improve the interior quality of deposited aluminum alloy parts with appropriate temperature condition by removing some common defects. Nevertheless, they were not concerned with the effects of substrate on the microstructure and performances of formed components. In addition, most researchers pay more attention to the numerical modeling of the thermo-mechanical behavior during the laser additive manufacturing process, but not focus on the influences of substrate temperature on this heat history [15–19]. In this work, combined with the numerical simulation model, the LMDS system and a self-developed substrate preheating facility were employed to intensively investigate the effects of substrate preheating on the as-deposited metal parts.

2. Experimental details

2.1. Experimental condition

In view of the practicability and typicality of the material, Ni60A alloy powder with 200 mesh particle size was chosen as the experimental material, and Q235 steel with different thickness was taken as the substrate material. The element contents of Ni60A alloy and Q235 steel are exhibited in Table 1.

The laser rapid manufacturing equipment exhibited in Fig. 1(a) was developed in Shenyang Institute of Automation, Chinese Academy of Science, which is named Laser Metal Deposition Shaping (LMDS) system. It consists of a 3 kW continuous wave CO₂ laser, a NC system including an industrial control computer, a PCI-1240 motion control card and a six-axis NC machine tools, and a powder feeding system containing a two-stockhouse storage and feeding system and a coaxial powder nozzle.

In addition, a set of substrate preheating facility attached to LMDS system was devised in terms of the processing characteristics and heat transfer theory. It was integrated with an intelligent PID controller and a computer serial temperature collecting device. Accordingly, it could realize dual-channel control and continuous adjustment of substrate preheating temperature, as well as real-time acquisition and record. The hardware was mainly composed of substrate preheater, intelligent PID controller and realtime acquisition and feedback control system, as shown in Fig. 1(b). This substrate preheating facility was named SP-SIA100, and its related parameters are listed in Table 2.

2.2. Experimental procedure

The whole experimental process was conducted with the protection of argon. In order to investigate the effects of substrate preheating temperature on the deformation and crack of as-fabricated parts, Ni60A powder and thin substrates (2 mm) of Q235 steel were used to carry out the same multilayer cladding, namely thin-wall part experiments five times with the substrate non-preheated and preheated to 300 °C, 400 °C, 500 °C, 600 °C, respectively, and other processing parameters were identical.
3. **Numerical simulation model**

In accordance with the experimental procedure, the corresponding numerical simulation model was established through the simulation software of finite element method (FEM). Then, the heat transfer characteristics between deposited material and substrate were analyzed, the influence rules of substrate preheating on the thermal behavior during LMDS were investigated, and the distribution characters of temperature and stress field were mastered through the numerical simulation model. In addition, the experimental results regarding the deformation and crack of parts fabricated on the substrates with different preheating temperatures were used to verify the reliability and evaluate the validity of numerical model, so the model could play an important role in predicting experimental results and instructing processing technology. Furthermore, the effects of substrate preheating on the microstructure and properties of deposited samples were explored in accordance with the relevant testing techniques.

3.1. **Modeling with FEM**

According to the practical experiment conditions, a numerical simulation model was proposed to investigate the effects of substrate preheating on the LMDS process by employing the element birth and death technique of finite element analysis.

![Fig. 2. Schematic of the element birth and death approach for finite element analysis of laser powder deposition.](image)

3.1.1. **Element birth and death**

To calculate the temperature distribution and thermal stress in the part during the deposition process using the finite element method, the geometry of the part must be represented by a mesh of finite elements that changes over time to simulate the continuous addition of material. This time-dependent problem was solved sequentially, as a series of constant geometry problems (called steps), linked together by introducing the output of problem \( n \) as the initial condition for problem \( n + 1 \). This stepwise approach, called the element birth and death technique in FEM, is presented in Fig. 2, which could simulate the laser powder deposition process through the finite element analysis. The addition of material was modeled by activating a new group of finite elements at the beginning of each step. Then, the boundary conditions were updated according to the newly exposed surfaces. The total number of elements effectively activated at the beginning of each step is determined by the volume of material added during the corresponding time interval. This volume is closely related to the powder feeding rate, powder use efficiency and material density.

Accordingly, the activation of elements can be compared to the deposition of laser powder material. The buildup of elements represents the formation of part, so the finish of numerical simulation means that the fabrication of final part is completed.

3.1.2. **FEM model**

The dimensions of substrate and deposited metal part in the numerical model are illustrated in Fig. 3(a), which exhibits the front and top views of the FEM model. This model was created to simulate the cases that the samples were additively deposited on the various substrate preheating temperatures with four tracks and three layers every time. Fig. 3(b) represents the locations of nodes on longitudinal section. The model was built according to the long-edge parallel reciprocating scanning mode, as shown in Fig. 4. The processing parameters, namely laser power 800 W,
spot diameter 1 mm, scanning speed 5 mm/s, are assigned in this simulation process, which lasts 120 s.

3.2. Effects on temperature distribution

Fig. 5 describes the temperature contours of model with substrate non-preheating or preheating of 600 °C. As shown in Fig. 5(a), without the substrate preheating, the high-temperature area of the model mainly accumulates at the molten pool and its vicinity, which manifests the tailing shape. The difference in temperature between high-temperature area and substrate is extremely large. The temperature of most region of substrate is below 200 °C, while the temperature of proximity region of molten pool is commonly higher than 800 °C, and even more than 2000 °C at the molten pool. As exhibited in Fig. 5(b), when the substrate is preheated to 600 °C, the highest temperature of molten pool is promoted, and even up to 2800 °C. Besides, the relative high-temperature range in the vicinity of molten pool is narrowed down evidently, so the tailing appearance of high-temperature region is not obvious. Apart from the high-temperature molten pool, the difference in temperature between the proximity of molten pool and substrate is significantly reduced. This is beneficial to decrease the temperature gradient either in deposited sample or between sample and substrate, thus lessening the thermal stress in the laser additive manufacturing process.

Fig. 6 indicates the temperature gradient vectors of model without preheating or preheating of 600 °C. As shown in Fig. 6(a), the temperature gradient of numerical model is considerably great without the substrate preheating. The magnitude of temperature gradient in the just scanned region of depositing layer is very high, and the orientation of temperature gradient is distinctly inclined to the positive direction of Z axis. In contrast, the magnitude of temperature gradient in the region to be scanned of depositing...
layer is relatively low, and the temperature gradient in the positive direction of Z axis is faded down. As exhibited in Fig. 6(b), the temperature gradient of numerical model is remarkably reduced with the substrate preheated to 600 °C. The magnitude of temperature gradient in the just scanned region of depositing layer with the substrate preheated to 600 °C is even lower than that in the region to be scanned of depositing layer without the substrate preheating. In addition, the orientational trend in the positive direction of Z axis of temperature gradient in the just scanned region of depositing layer with the substrate preheated to 600 °C is weaker than that in the region to be scanned of depositing layer without the substrate preheating. With the substrate preheating of 600 °C, the magnitude of temperature gradient in the region to be scanned of depositing layer is much lower. The reason for explaining the phenomena in Fig. 6 is that the preheating process increases the temperature of substrate, decreases the temperature difference between sample and substrate, and notably reduces the temperature gradient in the fabricating process.

Fig. 7 depicts the temperature curves of the nodes in the first layer of the model with substrate non-preheating or preheating of 200 °C, 300 °C, 400 °C, 500 °C and 600 °C. As illustrated in Fig. 7, with the increase of substrate preheating temperature, the highest temperatures of nodes 1, 2 and 3 gradually rise, while the temperature variation ranges of them reduce step by step. This is consistent with the analytic results of temperature gradient. Besides, in the wake of promotion in substrate preheating temperature, the temperature variation curves of these nodes appear to be smoother by degrees, which could help in improving the uniformity of temperature distribution in the deposition process.

3.3. Effects on thermal stress

Fig. 8 demonstrates the Von Mise’s thermal stress curves of the nodes in the first layer of the model with substrate non-preheating or preheating of 200 °C, 300 °C, 400 °C, 500 °C and 600 °C. As shown in Fig. 8, with the different substrate preheating temperatures, all the Von Mise’s thermal stresses of node 1 are greater than that with substrate non-preheating when the first layer is deposited. In the process of deposition of successive layers, with the increase of substrate preheating temperature, the Von Mise’s thermal stresses of node 1 increase firstly and then decrease, and generate a fall of about 16.5 percent at preheating temperature of 600 °C. With the ascension of substrate preheating temperature, all the Von Mise’s thermal stresses of node 3 are also greater than that with substrate non-preheating as the second layer is deposited, but reduce quickly with the third layer, and induce a decrease of about 38.2 percent at preheating temperature of 600 °C. In addition, the variation range of Von Mise’s thermal stresses of node 2 is relatively limited with the enhancement of substrate preheating temperature.

Fig. 9 exhibits the X-direction thermal stress curves of the nodes in the first layer of the model with substrate non-preheating or preheating of 200 °C, 300 °C, 400 °C, 500 °C and 600 °C. As shown in Fig. 9, with the non-preheated substrate, the X-direction thermal stress of node 1 primarily manifests thermal shrinkage stress when the first layer is deposited, but gradually changes into tensile stress with the second layer. The substrate preheating accelerates this transformation. The X-direction thermal stress of node 2 basically represents the thermal shrinkage stress without the substrate preheating. However, with the increase of substrate preheating
Fig. 8. Von Mise's thermal stress curves of the nodes in the first layer of the model with substrate non-preheating or preheating of 200 °C, 300 °C, 400 °C, 500 °C and 600 °C.

Fig. 9. X-direction thermal stress curves of the nodes in the first layer of the model with substrate non-preheating or preheating of 200 °C, 300 °C, 400 °C, 500 °C and 600 °C.
temperature, this kind of shrinkage stress transforms into tensile stress step by step as the second layer is deposited, and the magnitudes of thermal stresses are aggregated. The X-direction thermal stress of the node 3 shows the thermal shrinkage stress. With the augment of preheating temperature, the magnitudes of this kind of stresses increase as the second layer is built, but decrease as the third layer is done, and produce a drop of about 16.5 percent at preheating temperature of 600 °C.

Fig. 10 represents the Y-direction thermal stress curves of those nodes in the first layer of the model with substrate non-preheating or preheating of 200 °C, 300 °C, 400 °C, 500 °C and 600 °C. As illustrated in Fig. 10, the substrate preheating changes the properties of Y-direction thermal stress of node 1 and node 2, and makes the transition of these nodes from the tensile stress with substrate non-preheating to the shrinkage stress with substrate preheating when the first layer is fabricated. With the increase of substrate preheating temperature, the magnitudes of Y-direction thermal stresses of node 2 show a decline in comparison with the case of substrate non-preheating, and generate a descent of about 25 percent at preheating temperature of 600 °C. As the substrate preheating temperature ascends, the Y-direction thermal stresses of node 3 increase substantially when the second layer is created, but decrease comparably with the third layer.

Fig. 11 demonstrates the Z-direction thermal stress curves of the nodes in the first layer of the model with substrate non-preheating or preheating of 200 °C, 300 °C, 400 °C, 500 °C and 600 °C. As shown in Fig. 11, the Z-direction thermal stresses of node 1 mainly manifest the tensile stress, whose magnitudes are very great. This is the main reason for crack and rapture of samples in the deposition process. With the growth of substrate preheating temperature, at fist the Z-direction thermal stresses of node 1 are equivalent to that with substrate non-preheating; next, the former are greater than the latter; at last, the former are smaller than the latter. As the substrate is preheated to 600 °C, the Z-direction thermal stress of node 1 is about 10.2 percent smaller than that without the substrate preheating. The Z-direction thermal stresses of node 2 primarily manifest the compressive stress, whose magnitudes are comparably small. In addition, the effects of substrate preheating temperature on these stresses are insignificant. The Z-direction thermal stresses of node 3 mainly show the shrinkage stress, whose magnitudes gradually increase with the ascent of substrate preheating temperature, but are substantially smaller than those of node 1.

4. Experimental results and discussion

4.1. Effects on deformation and crack

Fig. 12 indicates the LMDS-deposited samples formed on the thin substrates at different substrate preheating temperatures. As shown in the figure, the higher the preheating temperature, the thicker the thin-wall part. The reason is that the higher the temperature, the more powder melted into the molten pool, namely the higher the deposition rate. With the increase of the preheating temperature, the positive deflection became more significant. In the deposition process, the thermal expansion of the substrate upper surface was constrained by the lower surface with lower temperature, thereby generating the negative deflection tendency. In the cooling process, the heat current of the part was dispersed into
Fig. 11. Z-direction thermal stress curves of the nodes in the first layer of the model with substrate non-preheating or preheating of 200 °C, 300 °C, 400 °C, 500 °C and 600 °C.

surrounding circumstance. Accordingly, the thermal stress in the part was gradually transformed into tensile stress, and the positive deflection could be formed. At lower substrate preheating temperature, the positive deflection created in cooling phase was slightly greater than the negative one initiated in deposition phase, so the final state of substrate exhibits slight positive deflection. Whereas, at higher substrate preheating temperature, the preheating could considerably alleviate the temperature gradient, as well as the tensile thermal stress along horizontal direction. Besides, in the cooling phase, the severe temperature change and the increment of deposition height caused the tensile stress by the inner thermal stress to increase drastically. In addition, the higher the preheating temperature, the greater the volume of samples, the more significant the contraction of samples during cooling. As shown in Figs. 9–11, the contraction stress in X direction was the most remarkable and increases gradually with the enhancement of preheating temperature. This contraction of sample was restricted by the substrate, so the ends of substrate were drawn to upwarp by the contraction stress, thus generating the positive deflection. Moreover, in the vertical direction, the sides of the samples created quick heat dissipation and strong contraction. This contraction was also restricted by the substrate, which pulled the place where the substrate was metallurgically bonded with the sides of sample, and then produced the trend of positive deflection. As a result, the positive deflection produced in the cooling phase is substantially greater than the negative one generated in the deposition phase, and the substrate ultimately demonstrated distinct positive deflection. Additionally, the higher the preheating temperature, the more significant the positive deflection.

Fig. 12. Samples available at different substrate preheating temperatures (thin substrate).
Fig. 13 illustrates the surface finish of the parts built at varied substrate preheating temperatures. As shown in Fig. 13(a), there were several cracks (the white broken lines) on the surface of part gained with non-preheated substrate. In addition, uneven surface indicated the poor forming quality, and the measured value of surface roughness in this case is 100 μm. Fig. 13(c) demonstrates the part created on the substrate preheated at 600 °C. The higher part revealed the higher build rate, and the finer surface finish indicated the better forming quality. Under such circumstance, the test value of surface roughness is 60 μm. Fig. 13 displays the tendency that the higher the preheating temperature, the better the surface quality. It can be inferred from Fig. 8 that with the increment of preheating temperature, the Von Mise’s thermal stress of every node showed the trend of decrease. Accordingly, the substrate preheating was
beneficial to reduce the probability that the equivalent stress surpassed the yield strength, and even tensile strength, thus resulting in the failure and rupture of material. As indicated in Figs. 9–11, among the three principal stresses, the tensile stress in X direction was much greater than the other two directions. Since the tensile stress was the major cause of the fracture of material, the crack was prone to propagate along the direction vertical to X direction. In the process of deposition, with the increase of preheating temperature, each node possessed the tendency that the tensile stress in X direction decreased gradually, and even was transformed into the compressive stress. Consequently, the substrate preheating can effectively reduce the crack vertical to X direction to some extent.

4.2. Effects on microstructural morphology

The effects of substrate preheating on the microstructure and phase of as-deposited thin-wall parts were investigated with the similar experiments on the thick substrates. Fig. 14 shows the micro-morphology of cross sections of as-deposited Ni60A samples on the substrates with different preheating temperatures. The bright band in Fig. 14 is the solid solution interface between the clad and the substrate due to the mutual diffusion of alloy elements activated by the heat source, suggesting firm metallurgical bonding was formed between them. Additionally, it was the dividing strip for the laser-deposited clad and substrate, top of which was the laser rapid manufacturing material. As shown in Fig. 14, the higher the substrate preheating temperature, the coarser the morphology and the shorter the columnar dendrites at the bottom of the deposited materials. In contrast, the columnar dendrites at the top were fewer and even transited to equiaxial grains gradually. It can be explained that the lower the substrate preheating temperature, the greater the temperature difference between the substrate and the clad, which results in the higher temperature gradient in this direction. Comparatively, the higher the substrate preheating temperature, the smaller the temperature difference between the substrate and the clad, which induces the lower temperature gradient in this direction. The slower heat dissipation relaxed the solidification process. Therefore, the grains achieved more time to grow coarsely during the solidification process, and the solidification structure inclined to form equiaxial grains.

Fig. 15 represents the X-ray diffraction pattern of Ni60A clad, which indicates that the alloy phases are mainly composed of FeNi3 solid solution and some intermetallic compounds, such as Cr7C3, Cr23C6, CrB, Ni3B and Ni3Si. FeNi3 solid solution, namely γ-[Fe, Ni], is the matrix phase, while the other dispersed intermetallic compounds are the hard phases. These mesophases depicted, respectively, in Fig. 15(a) and (b) are basically the same, but the latters are relatively stable. With the increment of substrate preheating temperature, the transitions from metastable phases (Cr7C3 and Ni3Si) to stable phases (Cr3C2 and Ni3Si) in Fig. 15(b) should be attributed to the comparatively significant high-temperature annealing effect caused by the initial heat accumulation and the rhythmic heat transfer from the work-in-process layer to the previously deposited layers, especially the first layer combined with the substrate, during the layer-by-layer additive manufacturing. As illustrated in Fig. 15(a), without substrate preheating the crystal face (100) possesses the strongest diffraction peak intensity. Namely, the grains grew faster in the preferential crystal orientation (100) during the crystallization process, and formed the thin and thick dendrites paralleling with each other. It can be noted in Fig. 15(b) that with the growth of substrate preheating temperature, the diffraction intensity of the crystal face (100) decreases, while that of crystal faces (1 1 1) and (2 2 0) increases. It proves that the substrate preheating can cause the preferential orientation of directionally solidified crystal face to generate the branches, and even degrade the characteristics of directional solidification microstructure. Evidently, the higher the preheating temperature, the more disordered the growing directions of grains. Consequently, the microstructure growth tends to show up as the non-oriented polycrystalline features.

4.3. Effects on composition segregation

4.3.1. Plane analysis

The suitable positions (Fig. 16(a) and (b)) in the samples fabricated on different substrates were selected for the surface scan by EDS, and the experimental results are illustrated in Fig. 16(c)–(h). As shown in Fig. 16, the Cr, Ni and Fe elements in samples produced on the non-preheated substrate distributed uniformly, while those in samples manufactured on 600 °C preheated substrate distributed with segregation phenomenon. It proved that substrate preheating significantly affected the composition segregation and element distribution.

4.3.2. Line analysis

Fig. 17 depicts the line scan results of laser deposited metal parts fabricated on substrates at room-temperature and 600 °C. The lines in Fig. 17(a) and (b) denoted the line-scanning position
and path on microstructure. For the deposited material obtained on the substrate at room-temperature, the Cr and Ni elements of it distributed evenly on the scanning line (Fig. 17(c) to (f)). In contrast, for the deposited material on preheated substrate, the Cr and Ni elements scattered along the scanning line. This observation implied that high-temperature preheated substrate would lead to elemental segregation in the LMDS part, in comparison with the low-temperature or non-preheated substrate. For the
low-temperature or non-preheat substrate, the temperature gradient and cooling rate were both higher during the laser deposited process, the elements could diffuse rapidly in the dendrite arms and interdendritic zones, and the composition distributed more uniformly. Besides, the refined microstructure, namely close dendrite, generated by rapid solidification could relieve the degree of composition segregation. While for the parts formed on high-temperature preheated substrate, the dendrites were relatively short and sparse, and the top of the clad could even become equiaxial grains, which induced the composition segregation easily.

As shown in Fig. 17, along a same scanning line, the intensity of Cr signal increased with the decrease of Ni. Such phenomenon was caused by the different locations of the Cr-rich zones and Ni-rich zones in the part.

4.3.3. Point analysis

Fig. 18 displays the EDS point analysis results of the parts on different substrates. Fig. 18(a) indicates the element analysis at different locations of the parts deposited on the room-temperature substrate. It can be seen that the elements detected at different
points exhibited similar category and content, and no apparent composition segregation occurred. Fig. 18(b) shows the element analysis at different locations of the parts deposited on 600 °C preheated substrate. The diverse elements were detected at different points representing the variation of the compositions. The reason for this situation is that the high-temperature preheated substrate was easier to induce segregation phenomenon in the deposited material.

4.4. Effects on hardness

To confirm the effects of substrate preheating on the performance of the part, the hardness of 10-layer thin-wall parts fabricated on substrates preheated at different temperatures was measured. This effect can be observed in Fig. 19, where the final hardness profile with every layer along the wall height is presented for several values of the preheating temperature. It can be concluded that higher substrate preheating temperatures could improve the hardness and obtain more uniform hardness distributions because the hardening effect was more significant and the cooling period was longer when the material was deposited on higher temperature substrate. In addition, the hardness displayed a continuous rising trend along the wall height, because the deposited layer could cause tempering effect on the previously deposited layer, and degraded the hardness of these positions. It means that the higher the location of the wall, the lower the hardness. Independent of the preheating temperature, significant tempering occurred in the heat affected zone of the substrate, and decreased local hardness. These results show that the substrate preheating temperature could be adjusted to control the final structure and properties of parts.

4.5. Effects on mechanical properties

In order to master the effects of substrate preheating on mechanical properties of as-deposited parts, the thin-wall parts were fabricated layer by layer with the substrate non-preheated, namely at room temperature (about 20 °C), or preheated to 200 °C, 300 °C, 400 °C, 500 °C and 600 °C, respectively. Then, some tensile specimens were cut out from the thin-wall parts with their loading directions horizontal or perpendicular to the scanning direction, as shown in Fig. 20.
Next, these tensile specimens were loaded for mechanical tensile test. The experimental results were illustrated in Fig. 21, and the fracture morphologies of tensile samples were represented in Fig. 22. Accordingly, several important conclusions can be drawn in terms of these two figures.

First, the deposited thin-wall parts possess the remarkable anisotropy when fabricated on the low-temperature substrate. Fig. 21 exhibits the anisotropy of thin-wall parts derived from the oriented generation of columnar grains due to the temperature gradient in the height direction. Consequently, there are obvious variances in mechanical properties of samples with different positional relations between the scanning direction and the tensile direction. The mechanical strengths of tensile samples with horizontal relation are greater than those with vertical relation, but the contrary case happens to elongation. The reasons can be elaborated as follows. As for the horizontal relation in the former situation, the dendritic boundaries formed in these samples are primarily perpendicular to the loading direction, thereby hindering the dislocation movements, so the samples could bear larger load. This is the grain boundary strengthening mechanism in action. Since the deformations at the dendritic boundaries are restricted, the fracture would be generated along the grain boundaries even under the function of small strain, thus leading to the inferior elongation. In comparison with the vertical relation in the latter situation, the growth orientation of dendrites is parallel to the tensile direction of samples, so the dendrites tend to be lengthened under the effect of tensile stress, thereby resulting in the superior elongation. In addition, in this situation the fractures always occur in the remelting band, namely the bonding zone between the adjacent cladding layers. The reason for this is the weaker interlayer bonding strength and the microstructure differences between remelting band and depositing area. Consequently, influenced by the characteristics of microstructure, the samples deposited on the low-temperature substrate possess the remarkable anisotropy.

Second, Fig. 21 indicates that the increase of preheating temperature decreases the anisotropy of tensile samples. The reason for this is that as the preheating temperature climbs, the proportion of columnar grains in specimen decreases, while the percentage of equiaxed grains gradually increases due to the attenuation of temperature gradient in height direction. As shown in Figs. 14 and 15, this proportional change between columnar grains and equiaxed grains conduce to the tendency of transition from anisotropy to isotropy. The higher the preheating temperature, the weaker the temperature gradient. Accordingly, the more the equiaxed grains, the fewer the columnar grains. Essentially, in the wake of the growth of preheating temperature, the microstructure evolution is transformed from growth mechanism into nucleation mechanism, which weakens the characters of microstructure and properties in growth direction. As a result, with the increase of preheating temperature, the mechanical properties of tensile samples with different positional relations tend to uniformity and homogeneity. Namely, the variances in yield strength, tensile strength and elongation become smaller and smaller.

Third, it can be seen in Fig. 21 that as for the tensile specimens whose loading direction is parallel to scanning direction, with the increase of substrate preheating temperature the yield strength, tensile strength and elongation of the specimens all first rise then fall. With the ascent of preheating temperature, the microstructural evolution would be transformed from growth mechanism into nucleation mechanism due to the attenuated temperature gradient. The massive equiaxed fine grains are intricate and unordered, thus increasing the area and strength of grain boundary and decreasing the tensile stress between the neighboring grains. Then, the relief of tensile stress that is perpendicular to the growth direction of columnar grains could avoid the intergranular fracture between the adjacent dendrites. Furthermore, large quantities of equiaxed fine grains can improve the restriction of deformations at the dendritic boundaries, thus enhancing the ductility. As a result, as the preheating temperature rises up to 400 °C, the strength of grain boundary could be reinforced, and the mechanical properties would be promoted. However, with the further increase of preheating temperature, the grains would become coarse. The large grain boundaries between the adjacent coarse grains would be the places where the binding force is weak, so these places are easy to become the origination of cracks. This can deteriorate the mechanical properties. In addition, the high temperature reduces the resistance of dislocation movement, and the pinning effect of microdefects on dislocation would be alleviated, thus resulting in the deformation, yield and fracture of tensile samples. Therefore, the excessively high temperature could cause the degradation of mechanical properties. With regard to the tensile specimens whose loading direction is vertical to scanning direction, with the increase
of preheating temperature, the mechanical strengths of the specimens keep the ascending trend, but the elongation is prone to continuous descent, as depicted in Fig. 21. The main reasons are as follows. At low preheating temperature, in the deposited layers the metallic materials possess the favorable strength and ductility when stretched along the dendritic growth direction, but the interlayer bonding force of deposited samples is feeble. Moreover, there are different microstructures separately distributed in the bonding zone and adjacent deposited layers. The heterogeneous microstructures also deteriorate the interlayer strength. Accordingly, the tensile samples are prone to fracture at the interlayer, so their mechanical strengths would be degraded. However, the characteristic that the dendrites are facile to be stretched along their growth direction makes the tensile specimens with vertical positional relation possess the superior ductility and elongation. In the wake of the ascent of preheating temperature, the high temperature increases the depth of remelting band, thus realizing the adequate fusion and solidification at bonding zone and reinforcing the interlayer bonding strength. As a result, the firm metallurgical bond would be generated at the bonding zone. In addition, the high temperature is beneficial to the diffusion of components of deposited material, so the microstructures at bonding zone and its vicinity incline to homogeneity and uniformity, which reduces the adverse effect of microstructural differences on the bonding strength. Furthermore, the microstructure evolution would be transformed from columnar grains with growth mechanism into equiaxed grains with nucleation mechanism, thus producing the intercrystalline strengthening effect. In general, in this case only when the tensile stress is beyond the intragranular strength, can the transgranular fracture be produced. With the further elevation of preheating temperature, though the coarseness of grains could have an unfavorable effect on the mechanical strengths of deposited materials, the positive factors produced by temperature rising play a dominant role in this process. Consequently, the mechanical strengths of tensile samples with vertical positional relation could be promoted as the preheating temperature goes up.

![Mechanical strength and elongation vs. preheating temperature](image)

**Fig. 21.** Effects of substrate preheating temperature on the mechanical properties of tensile specimens whose tensile direction is horizontal or vertical to the scanning direction. (a) Mechanical strength; (b) elongation.
Besides, in the whole process of preheating temperature rising, the proportion of columnar grains becomes smaller and smaller, so the character of excellent ductility and plasticity along the dendritic growth direction fade away. The coarse grains deform nonuniformly, and are prone to stress concentration. The large and smooth grain boundaries are disadvantageous to prevent the dislocation glide and crack propagation, thus reducing the ductility and plasticity of tensile samples. Accordingly, the elongation of samples with vertical positional relation tends to continuous decrease with the increase of preheating temperature.

Fourth, it can be observed from Fig. 22 that the differences in fracture morphologies of tensile samples fabricated with substrate temperature of 20 °C between parallel positional relation and vertical one are more obvious than those deposited with substrate temperature of 600 °C. It proves that the temperature rising is beneficial to reduce the variances in fracture morphologies of tensile samples with different positional relations. Fig. 22 indicates that the fracture morphologies of as-deposited tensile samples with different positional relations and substrate temperatures all show up as ductile fracture. In addition, the size and depth of dimples on fracture surface of tensile samples fabricated with substrate temperature of 600 °C are greater than those manufactured with substrate temperature of 20 °C. Moreover, the abundant tearing ridges accumulate on the fracture surface of tensile samples fabricated with substrate temperature of 600 °C. These cases prove that the parts built with high-temperature substrate possess better ductility and plasticity, as well as higher uniformity and homogeneity. With regard to the tensile samples created with the vertical positional relation and the substrate temperature of 20 °C, though they have excellent elongation due to the dendrites with vertical growth direction, the rupture generally occurs at the bonding zone because of the weak bonding force. Accordingly, there are few big and deep dimples distributed on the fracture surface, as shown in Fig. 22(b). However, with the increase of substrate preheating temperature, the fracture morphology may be composed of plentiful dimples with greater size and depth, as exhibited in Fig. 22(d). It proves that in this case the fracture cannot be generated at the bonding zone any more, and the typical transcrystalline rupture would take place.

Summarily, the substrate preheating is beneficial to reduce the anisotropy of materials, so the microstructure and properties tend to be more homogeneous and uniform. However, the preheating temperature should be suitable. The excessively high temperature would degrade the mechanical properties, and generate some defects, such as powder adhesion, overheating and overburning.

5. Conclusions

It is confirmed experimentally that the conclusion that the substrate preheating temperature significantly affects the surface quality, microstructure and performance of as-formed parts can be drawn.

1) By virtue of the element birth and death technique of finite element analysis, the 3D multi-track and multi-layer numerical simulation model with different substrate preheating temperatures during Laser Metal Deposition Shaping was established through APDL programming method. According to this model, the effects of substrate preheating temperature on the heat history, temperature gradient, Von Mise's thermal stress, X, Y and Z direction thermal stress in the deposition process were comprehensively mastered. As the preheating substrate continuously increases, the highest temperature of molten pool goes up. The relative high-temperature area in the vicinity of molten pool lessens distinctly, so the tailing phenomenon of

Fig. 22. Fracture morphology with the tensile direction parallel or vertical to the scanning direction at different substrate preheating temperatures. (a) 20 °C (parallel); (b) 20 °C (vertical); (c) 600 °C (parallel); (d) 600 °C (vertical).
high-temperature region is inconspicuous. The temperature in the region near the molten pool relatively increases, but the temperature difference between the substrate and the region in the vicinity of molten pool significantly decreases. With the ascent of preheating temperature, the temperature variation curves of each node located at the longitudinal section of model become smoother and smoother. In addition, the temperature gradient of numerical model in the fabrication process decreases remarkably. The substrate preheating makes the variations of thermal stress curves, including Von Mises, X, Y and Z directions, of each node smoother. As can be seen from the equivalent stress diagram, the equivalent stresses of each node tend to decrease with the increase of preheating temperature. Evidently, the substrate preheating is beneficial to reduce the risk of the yield and fracture of material resulted from the occasion that the equivalent stress surpasses the yield strength, and even the tensile strength.

To some degree, the higher the substrate preheating temperature, the better the surface quality, the coarser the morphology and the shorter the dimension of the columnar dendrites at the bottom of the laser deposited materials. In contrast, the columnar dendrites at the top of the part were fewer and even transited to equiaxial grains gradually. Furthermore, the LMDS process with the high-temperature substrate was easier to exhibit segregation phenomenon than that with the low-temperature one. As well as other deposition parameters such as laser beam power, powder feed rate and scanning speed, the substrate preheating could be adjusted so as to optimize the build rate and surface finish. Besides, substrate preheating had additional advantages of reducing residual stresses and the consequent risks of thermal distortion and cracking. The hardness experiment showed that higher preheating temperatures would eventually lead to harder parts and more uniform hardness distributions, and the hardness along the wall height increased gradually. Without the substrate preheating, the parts built by LMDS have the remarkable anisotropy, so the effects of preheating temperature on mechanical properties are intimately related to the orientation. With respect to the specimens whose tensile direction is parallel to the scanning direction, with the ascent of preheating temperature, the mechanical properties show the variation tendency of falling after rising. In contrast, as for the samples which were stretched in the direction vertical to the scanning direction, the mechanical strengths appear to be an upward trend as the preheating temperature goes up, but the contrary case happens to the elongation. These influence regulations of preheating temperature are derived from the transformation of microstructure evolution. As a result, the substrate preheating would help to reduce the anisotropy of materials, and conduce to the uniformity and homogeneity of microstructure and performances. Besides, the increase of substrate preheating temperature is beneficial to reduce the variances in fracture morphologies of tensile samples with different positional relations, so the fracture morphology may be composed of plentiful dimples with greater size and depth. Overall, based on the above-mentioned influence rules, the substrate could be preheated to suitable temperature according to specific manufacturing requirements prior to the deposition process, which can definitely contribute to the microstructure and properties of the as-fabricated parts.

However, the preheating temperature should be restricted in a suitable range in case of the microstructure deterioration and roughness reduction due to the overheating, overburn, and powder adhesion.

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