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Thermal behavior and densification during selective laser melting of Mg-Y-Sm-Zn-Zr alloy: simulation and experiments

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Abstract
The temperature field and flow field during the selective laser melting (SLM) process of Mg-3.4Y-3.6Sm-2.6Zn-0.8Zr alloy were simulated by using a re-developed Fluent 17.0 commercial finite volume method (FVM). The surface tension, Marangoni convection, and the laser heat source with Gaussian distribution are taken into account. The effects of laser power and scanning speed on the temperature and the size of the molten pool are studied, and the influence of line energy density (LED) on the flow and densification behavior of the molten pool is also discussed. It shows that the temperature and the size of the molten pool are positively correlated with the laser power, and negatively correlated with the scanning speed. The LED affects the flow of the molten pool and the movement of the bubbles, thereby affecting the densification behavior. For an optimized laser power of 50 W and scanning speed of 0.4 m s\(^{-1}\), the bubbles can escape smoothly, the existence time of the molten liquid is 355.58 \(\mu s\) and a molded part with the optimal density (95.98 ± 1.4\%) is obtained. The experimental and numerical simulation results are in good agreement. It is concluded that a laser power of 50 W, and a scanning speed of 0.4 m s\(^{-1}\) are the optimal process parameters.

1. Introduction
As the lightest metal structural materials in industrial applications, magnesium alloys are widely used in aerospace, automotive industry, communication electronics and other fields because of their low density, good damping, high specific strength and specific rigidity [1–8]. However, the strength decreases significantly with the increase of temperature, magnesium alloys are difficult to be used as high temperature structural materials [9–11]. The addition of mixed rare earth elements can improve the high temperature mechanical properties of magnesium alloys [12, 13]. Therefore, the development of new rare earth heat-resistant magnesium alloy materials is one of the important topics in the research field of magnesium alloys in recent years. Rare earth heat-resistant magnesium alloys are usually produced by high-pressure casting. In casting, castings are prone to component segregation, shrinkage, porosity, pores, cracks and other defects, which seriously reduce the mechanical properties and corrosion resistance of magnesium alloys. Selective laser melting (SLM) technology is an additive manufacturing technology that directly manufactures metal parts. It can not only process complex shapes and structures that are difficult to achieve with traditional technology, but also produce high-density parts and reduce casting defects.

At present, the SLM technology has made great progress in titanium-based, iron-based, nickel-based and cobalt-based alloys such as Ti6Al4V [14, 15], 316L steel [16, 17], Inconel 718 [18, 19], Co-Cr alloy [20, 21]. The SLM process of traditional commercial magnesium alloys such as AZ91D and ZK60 has also been studied [22, 23]. However, there is no relevant report on the SLM process of multi-component mixed rare earth magnesium alloys.

The forming quality of SLM is closely related to the metallurgical dynamics in the molten pool. The liquid molten pool undergoes a process of rapid melting and rapid solidification. It is generally difficult to observe the transient temperature field and the dynamic behavior of the molten pool through experimental means. Numerical simulation can study the temperature field, the melting behavior of powders and the flow of the molten pool, etc in the SLM process efficiently and at low cost. It can reveal the inherent physical laws of the process and better control
the process. There are many factors that affect the SLM process. Among them, the laser power and laser scanning speed are the most significant process parameters that affect the SLM process [24].

In this study, the multi-element mixed rare earth magnesium alloys of Mg-3.4Y-3.6Sm-2.6Zn-0.8Zr was used as the powder materials. The temperature field and flow field were simulated and studied, using Fluent 17.0 commercial finite volume method (FVM). The effects of laser power and scanning speed on the temperature and the size of the molten pool were studied, and the influence of line energy density (LED) on the flow and densification behavior of the molten pool was discussed. The simulation results were also verified by experiments.

2. Model descriptions

Gambit 2.4.6 software is used for modeling and meshing. Fluent 17.0 software, which enables simulation of processes with molten metal flow and behavior of the bubbles, is introduced to simulate SLM process. The software was re-developed. And the user-defined functions (UDFs) for phase initialization, Gaussian heat source and Marangoni force were written. In order to simplify this problem, this research proposes the following assumptions: (1) The melt in the molten pool is assumed to be laminar and incompressible homogeneous Newtonian fluid [25], (2) The thermophysical parameters of metal powder materials have a piecewise linear relationship with temperature, (3) The powders have the same absorption rate of laser energy, and (4) The effect of the steam recoil pressure on the surface of the molten pool is ignored.

2.1. Physical model

The schematic diagram of the physical model in the SLM process is shown in figure 1. In the simulation, the laser beam is defined as a heat flow. This simulation uses a laser heat source with a Gaussian distribution as the incident heat source, and the heat source moves along the X-axis at a constant rate.

As shown in figure 1, the heat exchange includes: the heat absorbed by the powder, and the heat escaped to the external environment through thermal convection and thermal radiation. The two-dimensional size of the model is 0.8 × 0.2 mm, and the Gambit 2.4.6 software is used to divide the model grid into 2 μm structured grids. The grid division is depicted in figure 2. Set tracking point A, its coordinates are (0.0004, 0.00014). The powders have a radius of 5–20 μm and are randomly distributed, and the initial temperature of the powder layer is 300 K. A molten pool is formed under the action of the laser beam when the laser beam interacts with the powders, and the melt flows under the drive of gravity, surface tension and Marangoni force.
2.2. Governing equations

2.2.1. Mass conservation equation

The continuity equation is the equation of conservation of mass. Any flow problem must satisfy the law of conservation of mass. Expressed by the Hamiltonian differential operator, the fluid flow continuity equation is written as the following divergence form [26]:

\[
\frac{\partial \rho}{\partial t} + \text{div}(\rho \vec{u}) = 0
\] (1)

where \( \rho \) is the density, \( t \) is the time, and \( \vec{u} \) is the flow velocity in the molten pool.

2.2.2. Momentum conservation equation

(1) Momentum conservation equation in the X direction:

\[
\frac{\partial (\rho \vec{u} \cdot \hat{e}_x)}{\partial t} + \text{div}(\rho \vec{u} \cdot \hat{e}_x \vec{u} \cdot \nabla u_x) = \rho \hat{e}_x \nabla \cdot \vec{u} + S_x
\] (2)

(2) Momentum conservation equation in the Y direction:

\[
\frac{\partial (\rho \vec{u} \cdot \hat{e}_y)}{\partial t} + \text{div}(\rho \vec{u} \cdot \hat{e}_y \vec{u} \cdot \nabla u_y) = \rho \hat{e}_y \nabla \cdot \vec{u} + S_y
\] (3)

where \( u \) and \( v \) are the components in the X and Y direction respectively, \( \mu \) is the viscosity, \( P \) is the pressure, and \( S_x, S_y \) are the source terms of the momentum conservation equation in the X and Y direction respectively.

The momentum source term in this model includes surface tension and Marangoni force. The setting of surface tension adopts the continuous surface force (CSF) model that comes with Fluent 17.0, and then the surface tension coefficient is set. At the same time, the Marangoni force needs to be decomposed into X and Y.

The formula is as follows [27]:

\[
S = \left[ \frac{d\sigma}{dT} (\nabla T - \vec{n} (\vec{n} \cdot \nabla T)) \right] |\nabla \alpha_1| \frac{2\hat{\rho}}{\rho_1 + \rho_2}
\] (4)

where \( \vec{n} \) is the normal vector of the interface unit, \( \alpha_1 \) is the volume fraction of the metal phase, \( \rho_1, \rho_2 \) is the density of the metal phase and the argon phase respectively, and \( \hat{\rho} \) is the average density.

2.2.3. Energy conservation equation

\[
\frac{\partial (\rho T)}{\partial t} + \text{div}(\rho \vec{u} T) = \text{div}(\alpha g \nabla T) + S_H
\] (5)

where \( \alpha \) is the thermal conductivity, and \( S_H \) is the source term of the energy conservation equation in the X and Y direction. \( S_H \) can be expressed as follows:

\[
S_H = \frac{\partial (\rho \Delta H)}{\partial t} + \text{div}(\rho \vec{u} \Delta H)
\] (6)

where \( \Delta H \) is the latent heat of fusion.

2.2.4. Equations of volume of fluid (VOF) model

The VOF model is an interface tracking method under a fixed Euler grid, which can be used to track the interface between one or more mutually incompatible fluids. This simulation introduces the metal phase volume fraction \( \alpha_1 \) and the gas phase volume fraction \( \alpha_2 \) to describe the unit fluid, where \( \alpha_1 + \alpha_2 = 1 \). When \( \alpha_1 = 1 \), it means that all the inside of the grid is metal phase. When \( \alpha_2 = 0 \), it means that all the inside of the grid is gas phase. When \( 0 < \alpha_1 < 1 \), it means that there is both a gas phase and a metal phase inside the grid. This location is the interface between the two. The molten metal is assumed to be an incompressible fluid in the numerical calculation, so its divergence is zero, namely:

\[
\nabla \cdot \vec{u} = 0
\] (7)

The fluid equation used to describe the changes in the liquid or gas interface can be expressed as follows:

\[
\frac{\partial \alpha_1}{\partial t} + \nabla \cdot (\alpha_1 \vec{u}) = 0
\] (8)
2.3. Boundary conditions

a. The left and right sides and upper surface of the argon gas layer are set as velocity inlet boundary conditions.

b. The left and right sides and bottom surface of the substrate are the wall boundary conditions, and there are convective heat exchange, radiation heat dissipation, and heat loss between it and the protective gas.

c. At the phase interface, there is the input of Gaussian heat source, as well as the effects of convective heat transfer and radiation heat dissipation, which are reflected in the source term of the energy equation. The mathematical expression is

$$-k \frac{\partial T}{\partial y} = q_{\text{laser}} - q_{\text{convexion}} - q_{\text{radiation}}$$

where $q_{\text{laser}}$ is the Gaussian heat source, and C language is used to realize that the Gaussian laser heat source moves at a constant speed along the X direction. $q_{\text{convexion}}$ and $q_{\text{radiation}}$ are the energy escaped through thermal convection and thermal radiation, respectively. They can be defined by

$$q_{\text{laser}} = \frac{2\eta P}{\pi R^2} \exp \left( -\frac{2r^2}{R^2} \right)$$

$$q_{\text{convexion}} = h_c (T - T_{\text{amb}})$$

$$q_{\text{radiation}} = \sigma_s \epsilon (T^4 - T_{\text{amb}}^4)$$

where $\eta$, $P$, and $R$ are the laser absorption rate, laser power and laser radius, respectively. $r$ is the distance from a point on the powder bed to the center of the laser spot. $h_c$, $T_{\text{amb}}$, $\sigma_s$, and $\epsilon$ are the convection heat transfer coefficient, ambient temperature, Stephen-Boltzmann constant, and thermal radiation coefficient, respectively.

2.4. Numerical simulation

The simulation is carried out using the commercial software Fluent 17.0. And JMatPro software is used to calculate the thermophysical parameters of the material. The thermophysical parameters of Mg-3.4Y-3.6Sm-2.6Zn-0.8Zr are described in Figure 3. The as-used material properties and SLM processing conditions are shown in Table 1.
3. SLM experiments

3.1. Powder preparation

Mg-3.4Y-3.6Sm-2.6Zn-0.8Zr alloy powders were obtained by grinding and ball milling as-cast alloy ingots, and they were selected as the initial powder materials. The average size of the particles is 40 μm. The SEM diagram of the powder and the EDS chemical point A in (a) are shown in figure 4.

BLT-S210 was selected as the selective laser melting equipment, equipped with Nd:YAG laser with a wavelength of 1080 nm. The high purity argon (99.99%) was used as the shielding gas. The oxygen content in the forming chamber is about 10 ppm, the laser spot diameter (D) is 60 μm, the hatch spacing (S) is 80 μm, and the thickness of powder layer (T) is 20 μm. The substrate material is ZK61M, which has been preheated to 180 °C in the experiment. The studied process conditions are consistent with the data in the numerical simulation, as shown in table 1. The Archimedes drainage method was used to determine the relative density of SLM processed samples, and the metallographic test samples were cut, ground and polished according to standard procedures. The microstructure was characterized by GX51 metallurgical microscope.

4. Results and discussion

4.1. Temperature distribution and the size of molten pool

Figures 5(a) and (b) respectively depict the temperature distribution and the two-dimensions of molten pool under different laser powers (with fixed $v = 0.4 \text{ m s}^{-1}$). It can be seen from figure 5 that the temperature of the scanning area increases when the laser power increases from 40 W to 80 W. At the same time, the length of the molten pool gradually increased from 71.14 μm to 110.8 μm, and the depth of the molten pool enhanced from 21.62 μm to 31.9 μm. This is because the laser energy density in the laser action area increases and the powders can be fully melted.

Table 1. The as-used material properties and SLM processing conditions.

| Parameter                                | Value                  |
|------------------------------------------|------------------------|
| Laser absorptivity, η                   | 0.37                   |
| Laser power, P [W]                       | 40, 50, 60, 80         |
| Laser radius, R [μm]                     | 30                     |
| Laser scanning speed, v [m s⁻¹]          | 0.2, 0.4, 0.6          |
| Convective heat transfer coefficient, $h_c$ [W/(m²K)] | 15            |
| Ambient temperature, $T_{amb}$ [K]       | 300                    |
| The Stefan–Boltzmann constant, $\sigma_s$ [W/(m²K⁴)] | 5.67 × 10⁻⁸  |
| Radiation emissivity, ε                  | 0.4                    |
| Solid viscosity [kg/ m-s]                | 5                      |
| Liquid viscosity [kg/ m-s]               | 0.002                  |
| Shielding gas                            | Argon                  |

Figure 4. (a) SEM image showing the Mg-3.4Y-3.6Sm-2.6Zn-0.8Zr power, and (b) EDS chemical point A in (a). 3.2. Experimental procedures.
Figures 6(a) and (b) respectively show the temperature distribution and the two-dimensions of molten pool under different laser scanning speeds (with fixed $P = 50$ W). It can be seen from figure 6 that the length of the molten pool reduces from 110.08 $\mu$m to 27.24 $\mu$m, and the depth of the molten pool reduces from 38.24 $\mu$m to 4.22 $\mu$m when the scanning speed increases from 0.2 m s$^{-1}$ to 0.6 m s$^{-1}$. This is related to the temperature of the molten pool under the action of heat accumulation. When the scanning speed is relatively fast, the energy absorption in the laser action area decreases, and the absorbed energy is not enough to support its melting, so the size of the molten pool is reduced.

The temperature distribution of the Y = 0.00014 mm interface along the X direction under different laser powers (with fixed $v = 0.4$ m s$^{-1}$) and different scanning speeds (with fixed $P = 50$ W) is shown in figure 7. It can be seen from figure 7(a), when the laser scanning speed is constant, the maximum temperature of molten pool increases with the increase of laser power. The higher the laser power and the more heat input. When the
laser power is 80 W, the molten pool temperature reaches 1292.54 K. In this case, the over melting phenomenon will occur, and the powder melting is accelerated, which is easy to produce pores. At the same time, the temperature gradient is $1.47 \times 10^7 \text{ K m}^{-1}$, forming a high stress field, and the formed parts are easy to deform and crack under this high stress field [30]. When the laser power is 40 W, the heat input is too low and the powder absorption is insufficient. The highest temperature of the molten pool is 916.206 K, close to the melting point of 904.05 K. As a result, the surface tension of molten pool increases, which is not conducive to the lubrication behavior of molten pool. Consequently, the solidification process is dominant, and spheroidization

Figure 6. (a) Temperature distribution of molten pool under different laser scanning speeds (with fixed $P = 50$ W), and (b) The two-dimensions of melt pool under different laser scanning speeds (with fixed $P = 50$ W).
is prone to occur, which has an impact on the quality of the formed parts [31]. When the laser power is 50 W and 60 W, the maximum temperature is 1014.32 K and 1070.43 K, respectively. Therefore, the appropriate laser power should be selected.

On the other hand, it can be seen from figure 7(b) that when the scanning speed increases from 0.2 m s⁻¹ to 0.6 m s⁻¹ (with fixed P = 50 W), the maximum temperature of the molten pool decreases from 1058.36 K to 960.75 K. When the laser scanning speed is high, the heat of the laser heat source can not be fully absorbed by the powder layer, and the powder particles cannot be completely melted, which will affect the combination of the molten powders and the substrate, thereby reducing the quality of the formed parts. When the laser scanning speed is too slow, the powder particles will absorb more energy, which is easy to produce over burning phenomenon. Therefore, the appropriate size and temperature of the molten pool can be obtained by designing the appropriate laser processing parameters, so as to obtain the SLM parts with excellent quality.

4.2. Flow field description and densification behavior

In order to explore the flow law of molten pool, the linear energy density (LED) is introduced, which is the ratio of laser power to laser scanning speed. The influence of LED on convection and bubble migration in molten pool was studied. The velocity vectors of the molten pool under different LEDs is shown in figure 8 (with fixed v = 0.4 m s⁻¹). With the increase in LED from 100 to 200 J m⁻¹ (laser power from 40 to 80 W), the convection area of the molten pool increases, and the fluid in the molten pool flows to the front and back of the molten pool respectively. According to figure 7(a), when the scanning speed is 0.4 m s⁻¹, with the increase of laser power, that is, with the increase of LED, the higher the surface temperature of molten pool, the greater the temperature gradient. There is a negative correlation between surface tension and temperature. Therefore, the higher the temperature is, the smaller the surface tension is, and the greater the gradient of surface tension is. Larger temperature gradient and surface tension gradient are favorable to the formation of Marangoni convection. Marangoni convection not only accelerates the heat and mass transfer in the molten pool, but also provides the possibility of bubbles from the bottom of the molten pool to the top surface. As shown in figure 8(a), the LED is small, which is 100 J m⁻¹. The Marangoni convection is weak and the melt viscosity is high due to the lack of energy absorbed by the molten pool. The bubbles are not easy to escape out, so they stay in the molten pool and reduce the relative density of the molten pool. With the increase of LED, the molten pool can absorb enough energy. As a result, the melt viscosity decreases and the Marangoni convection increases. Therefore, the bubbles can get greater speed to escape smoothly, thus obtaining a compact molten pool and excellent surface quality, as shown in figure 8(b). As LED further increases to 150 J m⁻¹ or 200 J m⁻¹, as shown in figures 8(c) and 8(d), respectively. The Marangoni convection vortex is formed in the molten pool due to excessive energy absorption, which is not conducive to the escape of bubbles. The dense layer may not be formed in the molten pool due to the existence of bubbles, which leads to the decrease of the relative density after solidification. On the other hand, according to figure 7(a), when the LED is 200 J m⁻¹, the temperature gradient is too large, which is prone to form a high stress field. In this case, the formed parts tend to form cracks, thus the surface quality of the finished products is affected. By comparing the velocity vectors of the molten pool under different LEDs, it is found that when the LED is 125 J m⁻¹, the formed parts should have a good relative density.

It can be seen from figure 9 that the existence time of the molten liquid at the tracking point A increases with the increase of the LED, which is beneficial to the diffusion of the molten liquid. When the LED is 125 J m⁻¹, the molten liquid exists for 355.58 μs. When the LED is 100 J m⁻¹, the life of the molten pool is significantly...
shortened to 147.54 μs. At the same time, the temperature of the melt is difficult to reach the liquidus temperature and solidifies immediately at a high cooling rate \((1.11 \times 10^6 \text{ Ks}^{-1})\). At this time, the molten liquid material is insufficiently diffused, which will produce pores and reduce the density. When the heat input
increases to 150 or 200 J m$^{-1}$, the volume of the molten liquid increases, and the existence time increases to more than 1000 μs. The solidification process of the molten liquid is dominant, which is easy to produce spheroidization, and it is prone to affect the subsequent powders placement process and the relative density of the final formed part. Therefore, when the LED is 125 J m$^{-1}$, the molded part should have a good relative density.

4.3. Experiment verification

The scanning process diagram and the samples of SLM-processed Mg-3.4Y-3.6Sm-2.6Zn-0.8Zr are depicted in figure 10. And the metallographic micrographs of the samples with LEDs of 100 J m$^{-1}$, 125 J m$^{-1}$ and 150 J m$^{-1}$ were taken, as shown in figure 11. At a relative low LED of 100 J m$^{-1}$, a large number of bubbles are trapped in the molten pool, and the irregular pores appear after SLM, with an average size of 11.5 μm (figure 11(a)).
the applied LED is increased to 125 J m\(^{-1}\), there are a few residual pores in the solidified molten pool, and the average size is reduced to 4 \(\mu\)m (figure 11(b)). However, for relative high LED of 150 J m\(^{-1}\), bubbles tend to be trapped and remain in the molten pool, resulting in the aggregation of pores (figure 11(c)). When the LED is further increased to 200 J m\(^{-1}\), as shown in figure 7(a), a large temperature gradient appears in the temperature field, which is \(1.47 \times 10^7\) K m\(^{-1}\), which has an impact on the forming process, so the sample is not successfully made. The SEM images of the samples taken by Gemi\(\text{i}\) SEM 300 are shown in figure 12. It can more clearly characterize the distribution of the pores.

Figure 13 depicts the comparison of relative densities under different LEDs. The quantitative measurement shows that the best relative density can be obtained when the LED is 125 J m\(^{-1}\), which is (95.98 \(\pm\) 1.4)%.

Therefore, this model can accurately predict the temperature field and flow field of Mg-3.4Y-3.6Sm-2.6Zn-0.8Zr alloy during SLM process under different process parameters, so as to analyze the size and the flow phenomenon of molten pool.
5. Conclusions

The selective laser melting (SLM) process of the multi-element mixed rare earth magnesium alloys of Mg-3.4Y-3.6Sm-2.6Zn-0.8Zr has been simulated, using a finite volume method (FVM), and the main conclusions are as follows,

1. The size and temperature of molten pool are positively correlated with laser power and negatively correlated with scanning speed. As the laser power increases from 40 W to 80 W, the length and depth increase from 71.14 μm and 21.62 μm to 10.8 μm and 31.9 μm, respectively, and the peak temperature increases from 916.206 K to 1292.54 K. As the laser scanning speed increases from 0.2 m s⁻¹ to 0.6 m s⁻¹, the length and depth decrease from 110.08 μm and 38.24 μm to 27.24 μm and 4.22 μm, respectively, and the peak temperature decreases from 1058.36 K to 960.75 K.

2. The linear energy density has an effect on the flow of molten pool and the motion of bubbles. When the LED is 100 J m⁻¹, the melt viscosity is low and Marangoni convection is weak, so the bubbles are difficult to escape. And the life of the molten pool is 147.54 μs. At this time, the molten liquid material is insufficiently diffused, which will produce pores and reduce the relative density. When the LED increases to 150 J m⁻¹ or 200 J m⁻¹, Marangoni convection will be enhanced, but the Marangoni convection vortex will be produced, which is not conducive to the escape of bubbles. The dense layer may not be formed in the molten pool due to the existence of bubbles, which will lead to the decrease of density after solidification. At the same time, the volume of the molten liquid increases, and the existence time increases to more than 1000 μs. The solidification process of the molten liquid is dominant, which is prone to spheroidization, which easily affects the subsequent process of placing powders and reduces the density of the final molded part. When the LED is 125 J m⁻¹, the bubbles can escape smoothly, the molten liquid exists for 355.58 μs, and the molten liquid is fully diffused to obtain a good quality molded part. And it is verified through experiments that the relative density increases first and then decreases with the increase of LED. It is concluded that when the LED is 125 J m⁻¹, the best relative density is (95.98 ± 1.4)%.

3. It is very important to design the appropriate SLM process parameters to obtain the appropriate size and temperature of the molten pool, which is of great significance to study the flow of molten pool, improve the densification effect and obtain the forming parts with excellent quality. Through the combination of numerical simulation and experimental verification, it can be concluded that when the laser power is 50 W, the scanning speed is 0.4 m s⁻¹, that is, the LED is 125 J m⁻¹, the forming parts with good quality can be obtained. It shows that the process parameters are suitable for SLM forming of Mg-3.4Y-3.6Sm-2.6Zn-0.8Zr multi-element mixed rare earth magnesium alloy.

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References

[1] Guan Y C, Zhou W, Li Z L and Zheng H Y 2013 Femtosecond laser-induced iridescent effect on AZ31B magnesium alloy surface J. Phys. D: Appl. Phys. 46 425305
[2] Yeganeh M and Mohammadi N 2018 Superhydrophobic surface of Mg alloys: a review J. Magnes. Alloy 6 59–70
[3] Chen T J et al 2014 Effects of reheating temperature and time on microstructure and tensile properties of thixoformed AZ63 magnesium alloy Mater. Sci. Technol. 30 96–108
[4] Luo K, Zhang L, Wu G H, Liu W C and Ding W J 2019 Effect of Y and Gd content on the microstructure and mechanical properties of Mg-Y-RE alloys J. Magnes. Alloy 7 345–54
[5] Prasad B K, Narayan S P and Modi O P 2011 Microstructure and micromechanism maps to optimise useful deformation processing conditions in magnesium alloy Mater. Sci. Technol. 27 1639–47
[6] Antunes R A et al 2014 Materials selection for hot stamped automotive body parts: an application of the Ashby approach based on the strain hardening exponent and stacking fault energy of materials Mater. Des. 63 247–56
[7] Mordike B L 2001 Magnesium properties-applications-potential Mat. Sci. Eng. A. 302 37–45
[8] Joost W J and Krajewski P E 2016 Towards magnesium alloys for high-volume automotive applications Scripta. Mater. 128 107–12
[9] Association IM 1999 IMA ‘99: annual world magnesium conference: proceedings: the 56th annual meeting of the Int. Magnesium Association: presents magnesium into the next millennium Int. Magnesium Association June 6–8
[10] Polmear IJ 1994 Magnesium alloys and applications Mater. Sci. Tech-lond. 10 1–16
[11] Luo A A 2003 Recent magnesium alloy development for automotive powertrain applications Mater. Sci. Forum 57–66
[12] Wang W L, Qiu Y L et al 2018 Influence of Sm element on the microstructure and mechanical properties of Mg-Y-Zn-Zr alloys Mater. Technol. 52 405–10
[13] Wang M, Xiao D H and Liu W S 2017 Effect of Si addition on microstructure and properties of magnesium alloys with high Al and Zn contents Vacuum 141 144–51
[14] Zhang T et al 2019 Evolution of molten pool during selective laser melting of Ti-6Al-4V J. Phys.: Appl. Phys. 52 055302
[15] Ansari M J et al 2019 Investigation of SLM process in terms of temperature distribution and melting pool size: modeling and experimental approaches Materials 12 1272
[16] Dong Z et al 2019 Effect of heat spacing on melt pool and as-built quality during selective laser melting of stainless steel: modeling and experimental approaches Materials 12 50
[17] Ahmadi A et al 2016 Effect of manufacturing parameters on mechanical properties of 316L stainless steel parts fabricated by selective laser melting: a computational framework Mater. Des. 112 328–38
[18] Zhang D et al 2018 Thermo-fluid field of molten pool and its effects during selective laser melting (SLM) of Inconel 718 alloy Addit. Manuf. 21 567–78
[19] Zhang L et al 2018 Effect of heat input parameters on temperature field in inconel 718 alloy during selective laser melting J. Mater. Eng. 46 29–35
[20] Teng C et al 2017 Simulating melt pool shape and lack of fusion porosity for selective laser melting of cobalt chromium components J. Manuf. Sci. E-T. Asme. 139 011009
[21] Al Jabbari Y S, Koutsoukis T, Barmpagadaki X and Zinelis S 2014 Metallurgical and interfacial characterization of PFM Co–Cr dental alloys fabricated via casting, milling or selective laser melting Dent. Mater. 30 179–88
[22] Wei K W et al 2014 Effect of energy input on formability, microstructure and mechanical properties of selective laser melted AZ91D magnesium alloy Mat. Sci. Eng. A. 611 212–22
[23] Wei K W, Wang Z M and Zeng X Y 2015 Influence of element vaporization on formability, composition, microstructure, and mechanical performance of the selective laser melted Mg-Zn-Zr components Mater. Lett. 156 187–90
[24] Yuan P and Gu D 2015 Molten pool behaviour and its physical mechanism during selective laser melting of TiC/AlSi10Mg nanocomposites: Simulation and experiments J. Phys. D: Appl. Phys. 48 35503
[25] Courtois M et al 2013 A new approach to compute multi-reflections of laser beam in a keyhole for heat transfer and fluid flow modeling in laser welding J. Phys. D: Appl. Phys. 46 505505
[26] Dong W C, Lu S P, Li D Z and Li Y Y 2008 Numerical simulation of effects of the minor active-element oxygen on the Marangoni convection and the weld shape Acta. Metall. Sin. 44 249–56
[27] He Q Y et al 2019 Modeling and numerical simulation of selective laser melting: multiphase flow, heat transfer and solidification Proc. of the 15th China CAE Engineering Analysis Technology Annual Conf.
[28] Hussein A, Hao L, Yan C Z and Everson R 2013 Finite element simulation of the temperature and stress fields in single layers built without-support in selective laser melting Mater. Des. 52 638–47
[29] Li Z H et al 2018 Research on the thermal behaviour of a selectively laser melted aluminium alloy: simulation and experiment Materials 11 1172
[30] Dai D and Gu D 2014 Thermal behavior and densification mechanism during selective laser melting of copper matrix composites: simulation and experiments Mater. Des. 55 482–91
[31] Duan C H, Zhao M H and Luo X P 2020 Thermal behavior and densification mechanism during selective laser melting additive manufacturing of metal powder Int. Mater. Res. Express 7 116519