第 36 卷　第 12 期
2009 年 12 月
中　国　激　光
CHINESE JOURNAL OF LASERS
Vol. 36，No. 12
December，2009

文章编号： 0258-7025(2009)12-3192-12

Materials and Process Aspects of Selective Laser Melting of Metals and Metal Matrix Composites：A Review (Invited Paper)

L. Hao　S. Dadbakhsh

(*School of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter, United Kingdom*)

Corresponding author：*l. hao@ex. ac. uk*

Received October 13，2009

Abstract　Selective laser melting (SLM) is currently the subject of major research studies with the objective to directly manufacture high performance metal alloys and metal matrix composite (MMC) parts by consolidating metal and its composite powders. The successful fabrication of the parts by SLM is related with proper selection of materials and processing parameters to provide sufficient densification and consolidation of the powder materials and generate suitable microstructures and mechanical properties. It is also important to minimize or eliminate typical issues such as porosity，balling effect，and thermal stress associated with the powder melting and consolidation at high temperature conditions during SLM process. This paper presents the fundamental material and process aspects，address the technical issues，and review the recent research development in the SLM of metal and MMCs.

Key words　additive manufacturing；selective laser melting；materials characteristics；process parameters；metal alloys；metal matrix composites

CLCN：TN249；TG146.4　　**Document Code**：A　　**doi**：10.3788/CJL20093612.3192

1　Introduction

Selective laser melting (SLM) is an additive manufacturing (AM) process and emerged as a new manufacturing technique to directly fabricate metal alloys and metal matrix composites (MMCs) products. SLM，termed direct metal laser sintering as similar to selective laser sintering (SLS)，is one of the most versatile AM processes to generate complex three-dimensional (3D) parts by solidifying successive layers of powder material on top of each other. It should be noted that while SLS uses sintering mechanism to partially melt and then fuse powder materials，SLM typically melts metal powders to fabricate parts for functional end-use applications. In SLM，a bed of metallic powders or metallic composite powders is melted by a beam spot laser projected from above and solidifies the powder layer. The powder-bed then drops down by a measure of one cross-section layer thickness. It is followed by an automated levelling system that distributes a new layer of powder over the top of the previous one. The laser then melts a new cross-section and the process is repeated to form a solid metal or MMCs part (comprised of hundreds or possibly thousands of thin layers) with good densities. The schematic pattern of the procedure and relevant scanning strategy is shown in Fig. 1[1~6].

Some benefits of SLM can be concluded as：1)

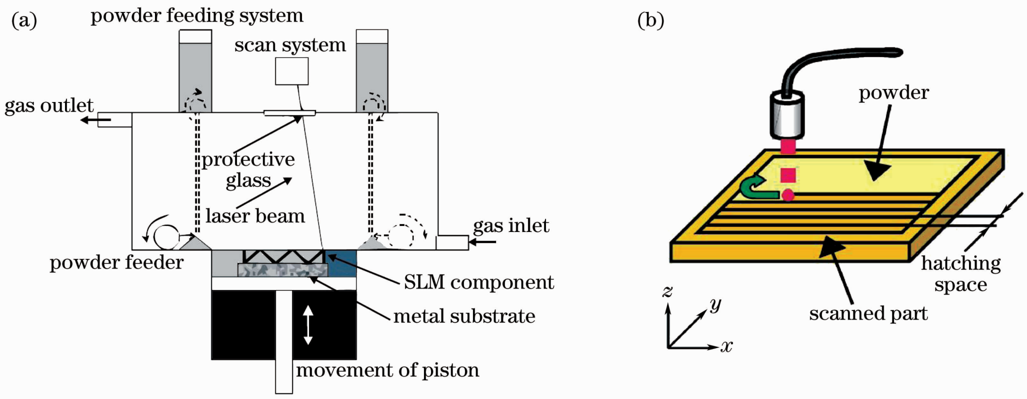

Fig. 1　Diagrams showing (a) how the SLM system works[5] and (b) laser scanning[6]

producing parts with high density and strength，2) negligible wastage of material，3) the ability to manufacture parts with complicated geometrical shapes，and 4) producing parts from a relatively wide range of metal alloys (e. g.，titanium，stainless steel，and cobalt-chrome alloys) and MMCs[1,4]. SLM parts are promising for various industrial applications，for instance，aerospace components with optimized geometry or lightweight structures；customised medical implants of complex stents，dental implants，and bridges[7]. However，many issues might be associated with the full melting of metal powders in the SLM process and result in the defects such as porosity，balling，delamination，and thermal stress in the SLM parts[8]. Hence，many research studies have been carried out to identify appropriate SLM processes，eliminate process issues，and develop new materials process capability. This paper aims to present three key areas of SLM research：1) describe and review the basic material and process aspects regarding SLM；2) discuss and address the technical issues associated with SLM；3) review the recent research development in the SLM of metal alloys and MMCs.

2 Fundamental of Material and Process Aspects of SLM

SLM is a complex thermo-physical process. An understanding of suitable materials，processing parameters，and environmental conditions is very important to manipulate the interactions of lasers and materials，and ensure good quality and properties of the SLM parts. This section briefly illustrates the roles of powder materials，SLM process parameters，and environmental conditions on the SLM.

2.1 Powder Material Characteristics

Characteristics of the material，especially those that control the thermal response of materials，such as melting temperature，transformation temperatures，thermal conductivity，specific heat capacity，thermal diffusivity，coefficient of thermal expansion，flow properties，laser absorption，latent heat of vaporization，etc.，originate from chemical composition and are the major parameters to select the appropriate method and parameters of powder bed laser processing. These properties affect crack sensitivity，porosity，HAZ embrittlement，poor absorption of the radiation，etc.[9].

The apparent density of powders，which is related to the powder size，shape，and size distribution，directly influence the final density of the SLM parts. Generally，packing of spheres leads to a higher density than other shapes. Moreover，finer powders result to a higher apparent density，meaning a higher final density and mechanical properties. For mono-sized spheres the best theoretical packing density obtainable is 74%. However，the apparent powder density can be enhanced by mixing different size powders. The principle involves using finer particles to fill the voids formed by the larger powders[10,11].

It is worthwile to note that as the size of particles decreases，the convective cooling rate increases，which contributes to a large undercooling in smaller particles. Large undercooling，in turn，produces a large driving force for solidification (nucleation) and results in a faster growth rate. In other words，as particle size decreases，the microstructural features become finer[12]，while finer microstructural features usually produce higher mechanical properties[13]. So，the refined microstructure due to the increasing cooling rate (smaller particles) increases the hardness of the powder particles.

Simchi ascertained another extra effect for particle size relating to densification kinetics in SLM[14]. He reported that finer particles provided lager surface area to absorb more laser energy，leading to a higher sintering rate. In fact，the sintering rate has a densification coefficient related to the powder characteristics (chemical composition，particle size，particle size distribution，oxygen content，etc.).

The heat treatment history of powder and its microstructure can significantly influence the phases after rapid melting and solidification due to laser melting. For example，some products from laser surface melting of stainless steels are explained as follow[9]. Fine structures are produced in both martensitic and austenitic stainless steels as expected from the high values of the cooling rate. Without the phase expansion associated with the martensitic transformation，austenitic steels have a residual tensile stress，while single tracks of martensitic steel are usually under compression，which becomes tensile when annealed by overlapping. The residual tension adversely affects the stress corrosion properties and the pitting potential.

Low viscosity is generally desirable for AM since this means that the material will flow easily. This is important for SLM since powder binding is critical for successful processing[15]. In addition to lower fluidity of liquid due to high viscosity, Rayleigh instability, which implies the break up of a liquid cylinder with high aspect ratio in order to lower the surface energy, increases with viscosity. This means that a higher viscosity (η) shows its negative influence with increasing the break time, resulting in larger droplets and balling of the melt[16].

2.2 Process Parameters

2.2.1 Energy Density Input: Laser Power, Scan Speed, Scan Line Spacing, Layer Thickness

Briefly, distortions like curling or delamination can appear due to the contraction of molten material that solidifies and cools down, and due to the high thermal gradients during SLM processes[17]. On the other hand, an optimal scan strategy and appropriate energy density can minimize these harmful effects. The energy density is an absolute process parameter representing the energy delivered to a unit volume of powder material and combining some important laser and scan parameters such as laser power, scan speed, scan line spacing, and layer thickness:

$$\eta = \frac{P}{vst}, \tag{1}$$

where η is energy density per volume (J/mm^3), P is laser power (W), v is scanning speed (mm/s), s is scan line spacing (hatching space) (mm), and t is layer thickness[18]. According to Eq. (1), increasing in laser power and decreasing in scanning speed, scan line spacing, and layer thickness can enhance the energy density of laser, which is necessary for melting of materials. In fact, the greater the energy imparted to the powder, the greater the particle fusion contributing to full melting is[19,20]. As it is mentioned, full melting has the main advantage of fabrication of a mostly dense product in one step, but it also has some disadvantages such as the high temperature gradients during the process involving internal stresses or part distortion[21], and the risk of balling and dross formation in the melt pool resulting in bad surface finish[1] requiring further process control. Development and repeating of some tests to compare parts can assist reaching optimal parameters. So some researchers have been occupied to achieve optimal parameters mostly in SLM technique of stainless steels, tool steels, and Ti alloys.

In general, higher energy density results to a denser material processed by SLM. However, at high laser energy inputs, delamination of layers and formation of large cracks are possible leading to the reduction of the density of parts. This phenomenon can be attributed to high thermal gradients in the materials accompanied by thermal stresses[14].

It is noteworthy that even at very intensive laser energy, full densification cannot be obtained because of delamination of the sintered layers due to thermal stresses, formation of gas pores during solidification, and porosity formation due to material shrinkage and the balling effect[14,22].

The layer scanning flow and solidification behaviour of the melt is strongly influenced by scan line spacing, in such a manner that a progressive transition from a highly rippled surface to a smooth surface occurs with decreasing in scan line spacing[23]. The formation of these continuous rows of metal agglomerates is related to the solidification of tracks of molten cylinder, while the formation of large inter-agglomerates pores can be attributed to tension effect and solidification shrinkage. Note that formation of metal balls due to instability of the molten cylinder according to Marangoni effect is likely to occur[14].

The amount, shape, and connectivity of pores are strongly affected by scan line spacing. Narrowing the scan line spacing makes the scan tracks close to each other and/or an increase in overlap. The overlapping of the tracks make it possible that larger parts of laser spot scan over the previously scanned track can lead to remelting of processed material. Therefore, the overlapping could result to the flowing and spreading of liquid between adjacent scan tracks and the escaping of some previously trapped air, and, hence, enhancement of the intertrack binding and reduction in the porosity[18].

It is worthwile to note that in laser sintering process, the duration of the laser beam at any powder particles is very short (<4 ms) and depends on scan rate and beam radius. Obviously, under this short heating cycle, the mechanism of particle bonding must be rapid and the solid state mechanisms are not feasible. Furthermore, with metals the viscous flow cannot result in powder densification since the viscosity is high, even at temperatures approaching the melting point. Thus, melting/solidification approach is the dominant mechanism for rapid bonding of metal powders in laser sintering[14,23,24]. Accordingly, one may expect the same trend of behaviour for the variation of density with energy of metallic parts manufactured by SLM, since melting/solidification mechanism is common in both the laser sintering and melting. In fact, this expectation can be conformed by the reports of other researchers such as Morgan *et al*.[8,25].

2.2.2 Frequency and Spot Size

Morgan showed that up to an energy density of approximately 7 J/mm^2, the sample produced at the lowest frequency exhibited the highest density while the continuous wave (CW) mode provided the lowest material density[8]. At these low energy densities, the size of the melt bead generated by the laser is small and hence leads to high porosity. The recoil compression effects associated with the low pulse rates is substantial enough to deform the melt bead, forcing it from a circular shape to a flatter profile and hence improving layer density. Beyond 7 J/mm^2 the energy density is sufficient to produce larger melt beads which bond with one another to produce a high density layer. Under such conditions, the effect of recoil shock induced deformation is less of a contributing factor in achieving high material density[8].

A laser beam is capable of being focused to a small spot size[26]. The spot size acts in two ways: a decrease in spot size firstly will increase the power density which affects the absorption; and secondly will decrease the affected area[9].

2.2.3 Scanning Strategy

Simchi carried out a series of experiments to assess the effect of three different scanning patterns (Fig. 2) on the density of rectangular specimens of iron powder[23]. The results demonstrated that the densification of the iron powder depended on the scanning pattern and the effect was less pronounced for specimens with high dimensional ratio y/x. Furthermore, higher sintered density was obtained when "Sorted" scanning pattern in x-direction (short scan vector) was used. In fact, the scan vector length strongly influenced the thermal history of the part in such a manner that, the sintered density was higher using short vector length (x-direction)[23]. It should be noted that the scan vector length influences the development of thermal stresses as well. These residual internal stresses reduce part performance. They also produce warp, loss of edge tolerance and delamination in parts[27]. Therefore, in laser sintering it is always preferred to use short vector length (x-direction).

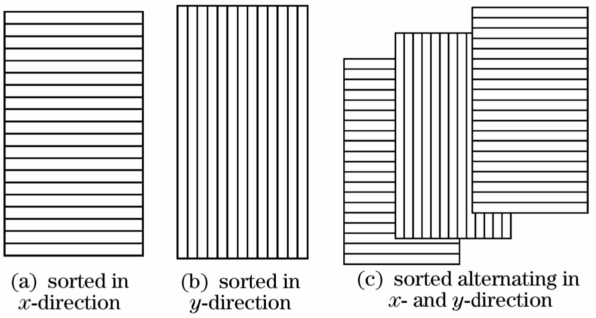

Fig. 2 Schematic of scanning patterns used in the mentioned study for direct laser sintering of iron powder (the scan line distances in x- and y- directions are equal). (a) short raster pattern in x-direction; (b) long raster pattern in y-direction; (c) alternating from layer to layer, starting with a short raster pattern for the first layer[23]

2.3 Environmental Conditions

Dust and smoke, vibration, and extreme temperatures can adversely affect laser operation. A careful assessment of the operating environment must be made. Suitably designed lasers should be used, and steps need to be taken to isolate sensitive lasers from unfavourable conditions[26].

It has been reported that the melting of iron powders in an argon atmosphere leads to a slightly better densification rather than nitrogen. Nevertheless, the effect of sintering atmosphere as compared to the other parameters is not very pronounced. The absorption of nitrogen in the iron liquid during the laser processing may serve some influence. The impact of sintering atmosphere on the densification could also be related to the amount of oxygen available during sintering. It is known that the presence of oxygen allows the formation of surface oxides and slag when the powder particles are heated and melted by the scanning laser beam. The formation of oxide layer on the surface of powder particles significantly increases the absorption rate of CO_2 laser radiation[14,23]. This changes the temperature-time history of sintering and increases the melt volume, allowing surface tension become more dominant. Another concern is the liquid metal surface tension, which influences the wetting angle between the solid and the liquid phases that can disrupt bonding between raster lines and individual layers[28]. Therefore, the amount of oxygen present during the heating, melting, and fusion of metal powders in the laser sintering process should influence the densification and the attendant microstructural features[14].

3 Potential Defects in the Parts Made by SLM

During the SLM process, metal powders are melted and consolidated under high temperature condition at very short interval time. This can lead to various issues for metal materials to densify appropriately and bond smoothly in the layer-by-layer building process. The typical defects such as porosity, hot tear, balling, and residual stress can be potentially generated in SLM process. The minimization and removal of these defects is very important to establish a successful SLM process.

3.1 Porosity Formation

Even when the particles are completely melted in the SLM process, porosity can be found due to trapped gas, shrinkage and etc, harming mechanical properties[29], etc. Adjustments of the laser processing parameters can improve the densification above 90% of the theoretical full density values. Porosity as a major problem in consolidation originates from the short material heating times caused by the scanning laser beam, relative to the time required for consolidation and the fact that there is no mechanical pressure (as in moulding processes). These facts can lead to porosity in parts. Post-processing is then required, if a pore-free material is needed[1]. Shrinkage microporosity in alloys is a result of a lack of feeding of the mushy zone, i.e., the density increase associated with solidification cannot be fully compensated by an interdendritic fluid flow[30]. Gas porosity is a special case of contamination. If porosity is found in any atomized powder, the first suspicion is always of gas solution in the melt, normally hydrogen, but possibly oxygen or steam. This defect usually occurs due to a reduction in solubility limit of gases such as hydrogen or nitrogen with decrease in temperature. In other words, with decrease in temperature, gas actual composition in the liquid increases and might exceed at some point their solubility limit, thus allowing pore nucleation. However, the contributions of gas diffusion and capillarity must be accounted for the nucleation and the growth of pores[31].

3.2 Hot Tearing

If microporosity is the major defect in shape casting, hot tearing is certainly the major defect of continuous or semi-continuous casting processes and of welding[32]. In fact, hot tear is a tensile creep-fracture created as the solid cools and shrinks[33], and develops due to the thermal stresses originating from the differences in thermal expansion[34]. Although hot tear occurs in large solidification interval alloys, similar to shrinkage-induced microporosity, but it involves tensile stresses in the partially coherent solid[32].

3.3 Balling

Balling can be a particular issue associated with the SLM process. The balling occurs when the molten material does not wet the underlying substrate due to the surface tension, which tends to spheroidise the liquid. This results in a rough and bead-shaped surface. The pool of molten metal must wet the previously processed metal below it. When it solidifies, its upper surface must be flat enough to enable a next layer of powder to be spread over it. Accordingly, the low wettability leads to not solid parts exhibiting a tendency of the melted powder to “ball up”. In fact, long thin melt pools are known to break up into balls, called “balling”[1].

During SLM process, a temperature gradient in the molten pool will be formed. The temperature gradients in the molten pool can increase surface tension and associate Marangoni convection. This results in balling to minimize surface free energy. This means the formation of spheres to reduce the surface area[23]. In addition to huge temperature gradient between the melting powder and the adjacent powder, the low viscosity of the material can lead to balling effects. In fact, when the viscosity is high, like in semi solid melts, sintering necks lead to stable sintering structures[35]. Generally, both materials properties and processing variables can influence wettability and consequently balling[1]. Also, as liquid metals do not wet surface oxide films in the absence of a chemical reaction, it is very important to avoid oxidation. Therefore sufficient remelting of the previous layer is necessary to remove surface contaminants, break down oxide films, and provide a clean solid-liquid interface at the atomic level. Another possibility to improve wetting is adding certain alloying elements, like phosphor in selective laser melting of iron-based powder[36]. Finally, a last method to suppress balling is applying very high pulse energies.

It has been reported that low scanning velocity and low laser power can promote the development and formation of semisolid conditions in the process zone, improving the bonding of stainless steel powders. That means the slow scanning velocities in combination with low laser powers are suitable to reduce balling effects. The explanation is seen in the moderate heating of the process zone and the related low and even distributed temperature. It is assumed that these conditions lead to semi solid metal and to a high viscosity which allows viscous sintering instead of balling[35].

Kruth *et al.*[36] have drawn a process window for continuous wave. This process window illustrated that high scan speeds combined with high laser powers result in less balling attributed to the melt pool which rapidly solidifies behind the laser spot, while the length of the molten track remains. In addition, high peak powers used in their process window study had a positive effect on the balling phenomenon since it could promote a good interlayer connection and result in a higher attained temperature of the melt[36].

3.4 Residual Stress

One of the major issues associated with the SLM is the residual stress remain inside of the parts which can cause delaminations, cracks, and deformation and also reduce fatigue strength when tensile stress remains in the part. Laser based processes (laser welding, SLM, etc.) are known to introduce large amounts of residual stress, due to the large thermal gradients which are inherently present in the processes. Two mechanisms can be distinguished that cause residual stresses. The first mechanism is called the temperature gradient mechanism (TGM, Fig.3(a)). Due to the rapid heating of the upper surface by the laser beam and the rather slow heat conduction, a steep temperature gradient develops. Since the expansion of the heated top layer is restricted by the underlying material, an elastic or even plastic compressive strain will be created. So, in the absence of mechanical constraints, a counter bending away from the laser beam may occur. The second mechanism, creating residual stresses in SLM, is due to the shrinkage of the molten layer(s) during cooling. With regards to this shrinkage, the newly deposited layer will be subjected to tensile stresses, with creating compressive stresses at the bottom[21,36].

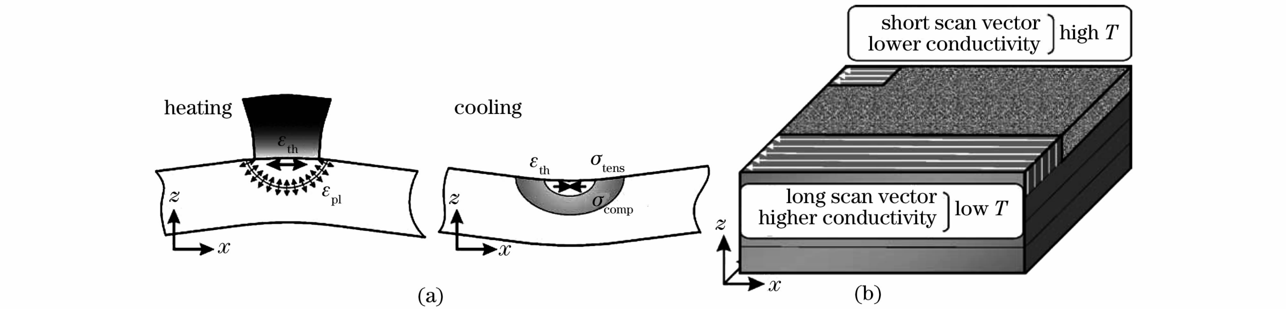

Fig.3 (a) Temperature gradient mechanism; (b) different temperatures through different scan vector lengths[36]

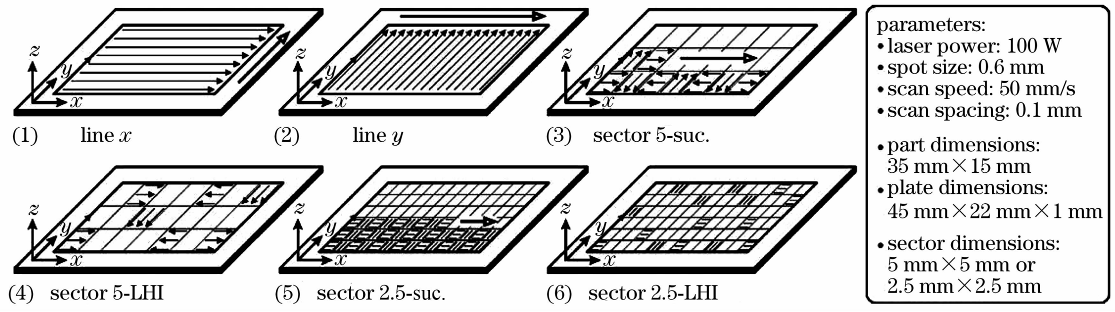

Fig.4 Six different scanning strategies used in the comparison[36]

In general, a small scanning area leads to high temperatures (Fig. 3(b)). For larger areas the laser beam travels much longer distances, resulting to a lower temperature of the scanned area. Consequently, lower wetting may happen, leading to a lower density of the material[36]. Accordingly, different scanning strategies and part sizes can lead to various residual stresses. For example, different scanning strategies and applied parameters shown in Fig. 4 can lead to various residual stresses and consequently part curvature. It has been reported that scanning along the x-direction resulted to the smallest curvature in that direction (1), but the largest curvature happened in the y-direction (vice versa for the y scanned part (2)). Applying the sector wise scanning (3)～(6) resulted to less deformation, though there are relatively small curvatures along x- and y-directions. No striking difference in curvatures between the (3) to (6) sector strategies can be found. Nevertheless, because of the shorter scan length (higher temperatures), a less laser energy input can be applied to obtain the same melting behaviour and the same temperature. This would further reduce the deformations caused by the TGM, which increase the benefits of smaller sectors[36]. In fact, the exposure strategy to fuse the powder layers influences the residual stress significantly[21].

With regards to the commonly unfavourable influences of residual stress on final quality of the parts, reduction of the residual stress arising from laser processes is usually desirable. The following instructions can be of help to reduce residual stress[21,36,37]:

1) Part removal drastically reduces the residual stresses present in the part. The residual stress after removal consists of a zone of tensile stress at the upper and lower zone of the part and a compressive stress zone in between. The stresses after part removal are much smaller than before part removal.

2) In general, the stresses are larger perpendicular to the scan direction than along the scan direction. A subdivision of the surface to smaller parts results to a lower residual stress level.

3) The more the number of additive layers is, the larger residual stress is.

4) It is possible to reduce the stress level by applying a heat treatment using the laser source.

5) Heating of the substrate plate results in a reduction of the residual stress level. This can be attributed to a reduction in temperature gradients due to the heating of subsurface plate.

6) Some post processing such as hot isostatic pressing (HIP), shut pinning, etc., can assist to reduce tensile residual stress.

4 Developments of SLM of Metal Alloys and MMCs

4.1 SLM of Advanced Metal Alloys

During the last couple of years, there has been increasing research work to develop SLM process of advanced metallic alloys including steel, cobalt, nickel, titanium, and aluminium based alloys. This has also driven the broad industrial applications of advanced metallic parts made by SLM process.

SLM of steel alloys have been subjected to an extensive research. A fundamental study has illustrated that the alloying elements (e.g., oxygen, carbon, silicon, titanium, and copper) can effect the binding and melt pool stability in SLM of steel powders attributed to their influence on physical phenomena of the process such as laser absorption, heat transfer, wetting and spreading of the melt, oxidation, Rayleigh instability, and Marangoni convention[16]. Experimental studies on M2 high speed steel, 316L and 314S-HC stainless steels have confirmed that variations of layer mass with scan speed are not consistent with what is expected from the delivered energy to the powder bed. In fact, the thermal history of processing is influential in determining the amount of melt under a laser beam irradiation[38]. A recent experimental study on the SLM of austenitic and Martensitic stainless steel powder mixtures with varying composition ratios have shown that the composition ratios of the mixed powder influence the laser consolidation mechanisms. The microstructural studies, as shown in Fig. 5, demonstrate that a new stainless steel grade can be produced via SLM process to have tailored mechanical and magnetic properties[39].

SLM of cobalt-chromium (Co-Cr-Mo) has been investigated for medical applications. For a long time, cobalt-chromium alloys have been the key materials for dentistry, and now they are also used for high-strength hip replacements and cardiovascular devices because of their high corrosion and fatigue resistance. It is reported that 99.9% dense Co-Cr-Mo parts can be fabricated using optimal SLM

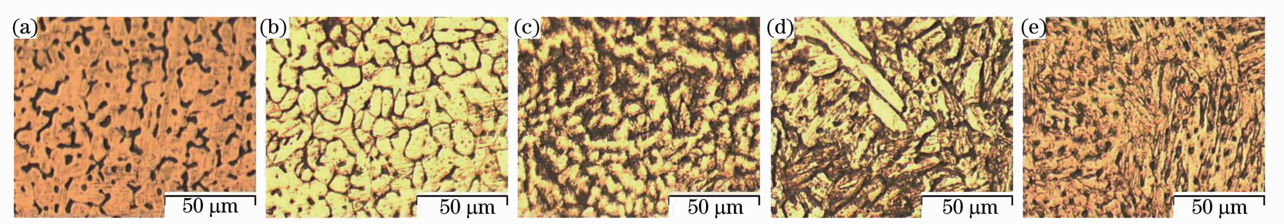

Fig. 5 Optical etched microstructures taken from below the lased surface of the 316L steel samples with (a) 0 wt.-% 17-4PH; (b) 25 wt.-% 17-4PH; (c) 50 wt.-% 17-4PH; (d) 75 wt.-% 17-4PH; (e) 100 wt.-% 17-4PH[39]

processing parameters and exhibit good mechanical properties such as hardness, strength, stiffness, and favourable corrosion behaviour[40], proving that SLM enables an efficient production of medical or dental parts with strong economical potential.

SLM of nickel alloys is also of subject of research attentions. Nickel-based alloy powders containing 83% Ni and 9.4% Cr are found to be suitable candidate for SLM process to directly make metallic parts such as die[6]. SLM has been applied to the manufacture cantilever beams of NiTi shape memory alloys for MEMS applications and induces a mixture of the martensitic and rhomboherdral R-phase in the alloy[41]. Experimental study has demonstrated the capability of SLM to fabricate high dense supernickel alloy Waspaloy up to 99.7% density using appropriate parameters (pulse width, pulse energy, repetition rate, and scanning speed) of a Nd:YAG laser[42].

SLM of titanium and titanium alloy is investigated intensively due to its promising applications in aerospace space and medical sector. The titanium specimens made by SLM using a Nd:YAG pulsed laser demonstrate approximately 240 HV hardness, higher than that of wrought material, and can have a comparable fatigue strength if the small hatching distance and hot isostatic pressing (HIP) are used[43]. The density of Ti6AL4V parts made by SLM is highly repeatable and controllable through the processing parameters in a commercial SLM machine (M3 liner machine, Concept Laser). Ti6AL4V parts with 99.98% density shows good mechanical properties including hardness, strength, stiffness, and corrosion resistance[40].

SLM of aluminium alloys has raised increasing research interest recently due to its lightweight property and relative low expense comparing to titanium alloy. The oxidation and high reflectivity of this material can cause issues in SLM process. A preliminary study showed that the pure aluminium powder can be fully melted in the SLM process, but the molten aluminium tends to agglomerate into globules due to the balling effect and possibly the existing oxide layer[44]. It has been reported that the aluminium 6061 powders can be fabricated by SLM process to achieve a maximum part density of 90% by using experimentally identified laser energy density and scan line spacing[45].

4.2 SLM of MMCs

As a powder based process, SLM provides the opportunity to consolidate second or multiple material particles with metal powders to form novel metal matrix composites and their products. The additional material elements influence the SLM process and its consolidation mechanism. They are also capable of tailoring the microstructure and consequently the properties of the resulting MMCs. Hence, there are increasing research effort to develop SLM process to fabricate MMCs, typically through ex-situ particle and powder blending approach and in-situ particle and powder interaction approach.

4.2.1 SLM of Ex-situ MMCs

The study on SLM of iron with graphite shows that homogeneous powder blends of 0.4, 0.8, 1.2, and 1.6 wt.-% graphite and iron can be processed EOS SLM system to produce 3D specimens. The graphite addition can increase the sintering kinetics of iron powder with using proper processing parameters. This significantly affects the resulting microstructure, which includes austentine and martensite structure, while it is very heterogeneous due to the very short laser interaction time[46].

With an objective to develop load-bearing implants, the SLM has applied to fabricate hydroxyapatite (HA) and stainless steel composites. It has been found that HA particles affect the melting and fusion of the stainless steel (SS) powder and dual scanning strategy needs to be applied in order to control the balling effects. As shown in Fig. 6, the SS/HA part has a finer grain size than that of the SS attributed to the HA particles as nuclei to assist het-

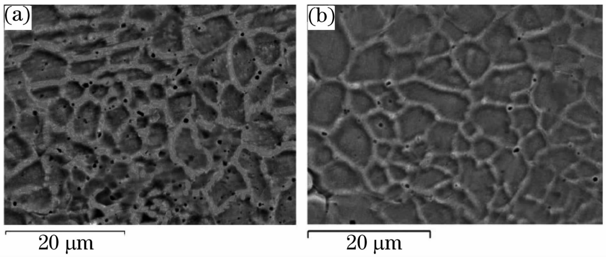

Fig. 6 Typical SEM view of (a) SS/HA and (b) 316L SS microstructure[20]

erogeneous nucleation. These finer grains enhance the hardness of the SS/HA part[20].

The study on SLM of submicron WC-Co particulate reinforced Cu MMCs shows that the sintering activity and densification response of the laser processed MMCs could generally become worse with a high weight fraction of reinforcement. This is due to a severe particulate aggregation and the resultant crack formation between the reinforcement and the matrix[47]. An addition of 1 wt.-% rare earth (RE) oxide (La_2O_3) into this WC-Co-Cu material system results in the improvement of densification, microstructure refinement, particulate dispersion homogeneity, and particulate/matrix interfacial coherence[48].

The study of SLM of Fe, Ni-TiC MMC shows that TiC particles can be homogeneously distributed with the Invar 36 metal matrix, however, the dissolution of Ti and C in the liquid of invar 36 alloy leads to spherical particles formation and cracking of the specimens. The low 30% TiC content needs to be used to produce crack free parts, but this results in the relatively low bending rupture strength and hardness[49].

SLM of ex-situ formed ceramic particulate reinforced MMCs, in general, does not give very dense products. Therefore, an extra material should be added such as La_2O_3 to the mixture of WC-Co and Cu, or the porous product have to be infiltrated[50]. But this will increase the complexity of the process to produce functional products.

4.2.2 SLM of In-situ MMCs

SLM can be used to induce chemical reactions between reinforcement particles and metallic powders to create in situ MMCs. The laser energy can be used to not only trigger the chemical reaction of the composites to form chemical compound, but also generate additional thermal energy to propagate melting and binding of particle powders. SLM of in-situ MMCs has significant benefits in terms of fine and uniform distribution of compound, inherent interface between reinforcement material and matrix and exothermic energy to facilitate melting and densification.

SLM is used to synthesise Cu-based MMCs reinforced with in-situ TiB_2 particles through the reaction among Cu, Ti, and B_4C using a 3-kW CO_2 laser. The in-situ reaction resulted in the formation of TiB_2 and non-stoichiometric TiC_{1-x} particles in a Cu matrix. Some porosity was observed in the Cu-Ti-B_4C system. However, with addition of Ni in the Cu-Ti-B_4C system, almost full densed parts could be obtained for the improvement of wetting[51,52].

SLM of TiO_2, Al, and C using a Q-switched Nd:YAG laser source can result in the combustion wave propagation of the self-propagating high-temperature synthesis (SHS) to in-situ form TiC-Al_2O_3 composites. Although some control over the SHS reaction has been achieved through 50% compaction of the reaction powders, there is further need to identify a proper operating window to control the reaction to produce a complex part. Further work is also required to increase the scanning speed since a threshold for the in-situ formation exists at scanning speed of 2 mm/s and power of 60 W. This is not a practical speed to build parts with a reasonable size[53].

SLM of high-energy mechanical alloyed Ti-Al-graphite elemental powder mixture is used to produce $TiC_p/(TiAl_3+Ti_3AlC_2)$ MMC part. The axial length of the laminated structure of the matrix is below 1.5 μm and the reinforcing particles are below 1 μm in size, though a slight grain growth occurs as relative to the starting nanocyrstalline powder[54]. As the applied laser powers increased, the TiC grain morphologies experienced successive changes from a laminated shape to an octahedron shape, and then a truncated near-octahedron shape, and finally a near-spherical one[55].

SLM of the high-energy ball milled Ti-Si_3N_4 composite powder with the mol ratio of 9∶1 has been used to synthesise TiN reinforced Ti_5Si_3 MMCs. It has been found that the in-situ formed TiN reinforcing phase has a refined granular morphology and a uniform distribution throughout the Ti_5Si_3 matrix, showing a clear and compatible interfacial structure with the matrix. The rapid cooling rate arising from SLM process gives insufficient time for the grain growth of TiN reinforcing phase, resulting in a refined morphology after solidification[56].

SLM of Al/Fe_2O_3 mixture has been used to directly fabricate in-situ Al MMCs. The visual inspection revealed that the Al/Fe_2O_3 mixture performed exothermic reaction in the SLM process and released the extra heat to cause eruptive spark and extend melting pool compared to pure Al in the SLM process, as shown in Fig. 7. Different microstructural structures were observed for the parts fabricated from Al and Al/Fe_2O_3 mixture. The Al part showed a dendritic structure while, in contrast, the part from Al/Fe_2O_3 mixture exhibited a granular structure, leading to more desirable mechanical properties. This was attributed to the role of in-situ formed components originating from the thermite reaction between Al and Fe_2O_3 acting as nuclei to facilitate heterogeneous nucleation[57].

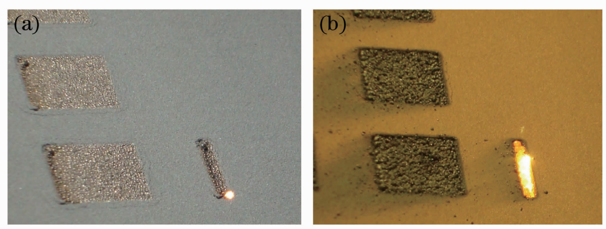

Fig. 7 Visual process development to fabricate single layer parts from (a) Al and (b) Al/Fe_2O_3 mixture using laser power of 38.5 W and scanning speed of 72 mm/s[57]

5 Summary and Future Research Aspects

SLM is emerged as a new additive manufacturing technique to directly fabricate metal alloys and MMCs products. Numerous researches have been performed to illustrate the fundamental effects of material characteristics and processing parameters, aimed to establish appropriate SLM parameters to produce quality and high performance metallic based parts. Due to the nature of the melting phenomena of the metallic powders, various issues can be associated with SLM process such as porosity, hot tear, balling, and residual stress. The SLM process needs to be carefully manipulated and controlled to minimize the potential defects.

SLM process has been used to fabricate a wide range of metallic alloys including steel, cobalt, nickel, titanium, and aluminium based alloys. This suggests a great commercial potential of the process as well as opportunities to develop advanced metal alloys and products. SLM process of MMCs is also very promising. Though there are some successes in the SLM of ex-situ mixed ceramic and metal powders, the products are still typically porous and require the modification of the process or infiltration post-process. In-situ formed MMCs in the SLM processes result from the chemical interaction of reinforcement and matrix materials. They normally possess refined microstructure, good particle/matrix interface, and excellent properties.

Still, SLM is a relatively new process and a subject for significant research efforts. Appropriate metallurgical understanding is required to illustrate the microstructure evolution and consolidation mechanism of metal alloy and MMCs powder materials in the SLM processes. The optimization and better control of the SLM process is critical to manipulate the microstructure, minimize the defects, and ensure the repeatable properties and quality of the parts. New material developments, including new metal alloys and MMCs, require in depth studies on the interaction of material and laser process and the relationship between materials-microstructures-properties. The understanding of rapid solidification mechanism in the SLM is another opportunity to further refine the microstructure composing of matrix and reinforcements. This opportunity for microstructural refinement can potentially lead to the generation of advanced nano-crystalline metal alloys or nano-particle reinforced MMCs.

References

1 J.-P. Kruth, G. Levy, F. Klocke *et al*.. Consolidation phenomena in laser and powder-bed based layered manufacturing [J]. *CIRP Annals-Manufacturing Tech*., 2007, **56**:730～759
2 F. Abe, K. Osakada, M. Shiomi *et al*.. The manufacturing of hard tools from metallic powders by selective laser melting [J]. *J. Mater. Process. Tech*., 2001, **111**(1-3):210～213
3 W. Meiners, K. Wissenbach, A. Gasser. Selective laser sintering at melting temperature[P]. U.S. 6,215,093, 1996
4 G. N. Levy, R. Schindel, J. P. Kruth. Rapid manufacturing and rapid tooling with layer manufacturing technologies, state of the art and future perspectives [J]. *CIRP Annals-Manufacturing Tech*., 2003, **52**(2):589～609
5 Ruidi Li, Yusheng Shi, Jinhui Liu *et al*.. Effects of processing parameters on the temperature field of selective laser melting metal powder [J]. *Powder Metallurgy and Metal Ceramics*, 2009, **48**(3):186～195
6 K. Osakada, M. Shiomi. Flexible manufacturing of metallic products by selective laser melting of powder [J]. *Int. J. Mach. Tools Manuf*., 2006, **46**(11):1188～1193
7 http://www.mtt-group.com/selective-laser-melting.html
8 R. Morgan, C. J. Sutcliffe, W. O'Neill. Density analysis of direct metal laser re-melted 316L stainless steel cubic primitives [J]. *J. Mater. Sci*., 2004, **39**:1195～1205
9 W. M. Steen. Laser Material Processing[M]. London:Springer-Verlag, 1991. 85,191
10 H. H. Zhu, J. Y. H. Fuh, L. Lu. The influence of powder ap-

parent density on the density in direct laser-sintered metallic parts [J]. *Int. J. Machine Tools & Manufacture*, 2007, **47**:294～298

11 J.-P. Kruth, B. Van der Schueren, J. E. Bonse *et al*.. Basic powder metallurgical aspects in selective metal powder sintering [J]. *CIRP Annals-Manufacturing Tech.*, 1996, **45**(1):183～186

12 M. Rajabi, A. Simchi, M. Vahidi *et al*.. Effect of particle size on the microstructure of rapidly solidified Al-20Si-5Fe-2X (X = Cu, Ni, Cr) powder [J]. *J. Alloys and Compounds*, 2008, **466**:111～118

13 G. E. Dieter. Mechanical Metallurgy [M]. Third ed.. New York: McGraw-Hill Book, 1986. 189～190

14 A. Simchi. Direct laser sintering of metal powders: Mechanism, kinetics and microstructural features [J]. *Mater. Sci. Eng. A*, 2006, **428**:148～158

15 D. L. Bourell. Rapid Manufacturing: An Industrial Revolution for the Digital Age[M]. N. Hopkinson. R. J. M. Hague and P. M. Dickens. West Sussex: John Wiley & Sons Ltd., 2006. 81～83

16 M. Rombouts, J. P. Kruth, L. Froyen *et al*.. Fundamentals of selective laser melting of alloyed steel powders [J]. *CIRP Annals-Manufacturing Tech.*, 2006, **55**(1):187～192

17 M. Matsumoto, M. Shiomi, K. Osakada *et al*.. Finite Element Analysis of Single Layer Forming on Metallic Powder Bed in Rapid Prototyping by Selective Laser Processing [J]. *Int. J. Machine Tools and Manufacture*, 2002, **42**(1):61～67

18 D. D. Gu, Y. F. Shen, J. L. Yang *et al*.. Effects of processing parameters on direct laser sintering of multicomponent Cu based metal powder [J]. *Mater. Sci. Tech.*, 2006, **22**:1449～1455

19 L. Hao, M. M. Savalani, Y. Zhang *et al*.. Selective laser sintering of hydroxyapatite reinforced polyethylene composites for bioactive implants and tissue scaffold development [J]. *Proc. IMechE Part H, J. Eng. Medicine*, 2006, **220**:521～531

20 L. Hao, S. Dadbakhsh, O. Seaman *et al*.. Selective Laser Melting of a Stainless Steel and Hydroxyapatite Composite for Load-Bearing Implant Development [J]. *J. Mater. Process. Tech.*, 2009, **209**(17):5793～5801

21 P. Mercelis, J.-P. Kruth. Residual stresses in selective laser sintering and selective laser melting [J]. *Rapid Prototyping J.*, 2006, **12**(5):254～265

22 A. Simchi. The role of particle size on the laser sintering of iron powder [J]. *Metal. Mater. Trans. B*, 2004, **35**(5):937～948

23 A. Simchi, H. Pohl. Effects of laser sintering processing parameters on the microstructure and densification of iron powder [J]. *Mater. Sci. Eng. A*, 2003, **359**:119～128

24 H. J. Niu, I. T. H. Chang. Liquid phase sintering of M3/2 high speed steel by selective laser sintering [J]. *Scripta Mater.*, 1998, **39**(1):67～72

25 J. W. Xie, P. Fox, W. O'Neill *et al*.. Effect of direct laser remelting processing parameters and scanning strategies on the densification of tool steels [J]. *J. Mater. Process. Tech.*, 2005, **170**(3):516～523

26 Laser Institute of America. LIA Handbook of Laser Materials Processing[M]. John F. Ready, Dave F. Farson (Editors), USA: Laser Institute of America-Magnolia Publishing Inc., 2001. 3,174

27 X. C. Li, J. Stampfl, F. B. Prinz. Mechanical and thermal expansion behavior of laser deposited metal matrix composites of Invar and TiC [J]. *Mater. Sci. Eng. A*, 2000, **282**:86～90

28 A. H. Nickel, D. M. Barnett, F. B. Prinz. Thermal stresses and deposition patterns in layered manufacturing [J]. *Mater. Sci. Eng. A*, 2001, **317**:59～64

29 S. Dadbakhsh, L. Hao, N. Sewell. A test procedure for mechanical qualification of additive layer manufacturing parts [C]. *Proceedings of the 10th National Conference on Rapid Design, Prototyping and Manufacturing*, 2009. 53～61

30 Campbell J. Castings[M]. Oxford: Elsevier, 2003

31 ASM Handbook. Powder Metal Technologies and Applications[M], Volume 7, ASM International, 1998

32 M. Asta, C. Beckermann, A. Karma *et al*.. Solidification microstructures and solid-state parallels: Recent developments, future directions [J]. *Acta Mater.*, 2009, **57**(4):941～971

33 M. F. Ashby. Materials Selection in Mechanical Design[M]. 3rd Edition, Elsevier: Butterworth-Heinemann, 2005. 180～182

34 P. Fox, S. Pogson, C. J. Sutcliffe *et al*.. Interface interactions between porous titanium/tantalum coatings, produced by Selective Laser Melting (SLM), on a cobalt-chromium alloy [J]. *Surface and Coatings Tech.*, 2008, **202**(20):5001～5007

35 F. Klocke, C. Wagner. Coalescence behaviour of two metallic particles as base mechanism of selective laser sintering [J]. *CIRP Annals-Manufacturing Tech.*, 2003, **52**(1):177～184

36 J. P. Kruth, L. Froyen, J. Van Vaerenbergh *et al*.. Selective laser melting of iron-based powder [J]. *J. Mater. Process. Tech.*, 2004, **149**(1-3):616～622

37 M. Shiomi, K. Osakada, K. Nakamura *et al*.. Residual Stress within Metallic Model Made by Selective Laser Melting Process [J]. *CIRP Annals-Manufacturing Tech.*, 2004, **53**(1):195～198

38 M. Badrossamay, T. H. C. Childs. Further studies in selective laser melting of stainless and tool steel powders [J]. *Int. J. Machine Tools and Manufacture*, 2007, **47**(5):779～784

39 P. G. E. Jerrard, L. Hao, K. E. Evans. Experimental investigation into selective laser melting of austenitic and martensitic stainless steel powder mixtures [J]. *Proc. IMechE Part B: J. Eng. Manufacture*, in Press

40 B. Vandenbroucke, J.-P. Kruth. Selective laser melting of biocompatible metals for rapid manufacturing of medical parts [J]. *Rapid Prototyping J.*, 2007, **13**(4):196～203

41 A. T. Clare, P. R. Chalker, S. Davies *et al*.. Selective laser melting of high aspect ratio 3D nickel-titanium structures two way trained for MEMS applications [J]. *Int. J. Mechanics and Materials in Design*, 2008, **4**(2):181～187

42 K. A. Mumtaz, P. Erasenthiran, N. Hopkinson. High density selective laser melting of Waspaloy? [J]. *J. Mater. Process. Tech.*, 2008, **195**(1-3):77～87

43 E. C. Santos, K. Osakada, M. Shiomi *et al*.. Microstructure and mechanical properties of pure titanium models fabricated by selective laser melting [J]. *Proc. IMechE Part C: J. Mechanical Eng. Sci.*, 2004, **218**(7):711～719

44 P. Jerrard, L. Hao, K. E. Evans. Selective laser melting of pure aluminium powder - A preliminary study[C]. *Proceedings of the 10th National Conference on Rapid Design, Prototyping and Manufacturing*, 2009. 45～52

45 M. Wong, S. Tsopanos, C. J. Sutcliffe *et al*.. Selective laser melting of heat transfer devices [J]. *Rapid Prototyping J.*, 2007, **13**(5):291～297

46 A. Simchi, H. Pohl. Direct laser sintering of iron-graphite powder mixture [J]. *Mater. Sci. Eng. A*, 2004, **383**(2):191～200

47 Dongdong Gu, Yifu Shen. Processing and microstructure of submicron WC-Co particulate reinforced Cu matrix composites prepared by direct laser sintering [J]. *Mater. Sci. Eng. A*, 2006, **435A-436A**:54～61

48 Dongdong Gu, Yifu Shen, Long Zhao *et al*.. Effect of rare earth oxide addition on microstructures of ultra-fine WC-Co particulate reinforced Cu matrix composites prepared by direct laser sintering [J]. *Mater. Sci. Eng. A*, 2007, **445A-446A**:316～322

49 A. Gåård, P. Krakhmalev, J. Bergström. Microstructural characterization and wear behavior of (Fe,Ni)-Ti MMC prepared by DMLS [J]. *J. Alloys and Compounds*, 2006, **421**(1-2):166～171

50 S. Kumar, J. -P. Kruth. Composites by rapid prototyping technology [J]. *Materials & Design*, in Press

51 C. C. Leong, L. Lu, J. Y. H. Fuh *et al*.. In-situ formation of copper matrix composites by laser sintering [J]. *Mater. Sci. Eng. A*, 2002, **338**(1-2):81～88

52 L. Lu, J. Y. H. Fuh, Z. D. Chen *et al*.. In situ formation of TiC composite using selective laser melting [J]. *Mater. Research Bulletin*, 2000, **35**(9):1555～1561

53 A. Slocombe, L. Li. Selective laser sintering of TiC-Al$_2$O$_3$ com-

posite with self-propagating high-temperature synthesis [J]. *J. Mater. Process. Tech.*, 2001, **118**(1-3):173～178

54 Dongdong Gu, Zhiyang Wang, Yifu Shen *et al*.. In-situ TiC particle reinforced Ti-Al matrix composites: Powder preparation by mechanical alloying and Selective Laser Melting behavior [J]. *Applied Surface Science*, 2009, **255**(22):9230～9240

55 Dongdong Gu, Yifu Shen, Guangbin Meng. Growth morphologies and mechanisms of TiC grains during Selective Laser Melting of Ti-Al-C composite powder [J]. *Materials Letters*, in Press

56 Dongdong Gu, Yifu Shen, Zhijian Lu. Preparation of TiN-Ti_5Si_3 in-situ composites by selective laser melting [J]. *Materials Letters*, 2009, **63**(18-19):1577～1579

57 S. Dadbakhsh, L. Hao, N. Sewell *et al*.. Direct fabrication of an in-situ Al composite using selective laser melting process [C]. *Innovative Developments in Design and Manufacturing: Advanced Research in Virtual and Rapid Prototyping - Proceedings of VR@P4*, Oct. 2009