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PROCESS OPTIMIZATION VARIABLES FOR DIRECT METAL LASER SINTERING

ABSTRACT

Manufacturing is crucial to creation of wealth and provision of quality of life. Manufacturing covers numerous aspects from systems design and organization, technology and logistics, operational planning and control. The study of manufacturing technology is usually classified into conventional and non-conventional processes. As it is well known, the term "rapid prototyping" refers to a number of different but related technologies that can be used for building very complex physical models and prototype parts directly from 3D CAD model. Among these technologies are selective laser sintering (SLS) and direct metal laser sintering (DMLS). RP technologies can use wide range of materials which gives possibility for their application in different fields. RP has primary been developed for manufacturing industry in order to speed up the development of new products (prototypes, concept models, form, fit, and function testing, tooling patterns, final products - direct parts). Sintering is a term in the field of powder metallurgy and describes a process which takes place under a certain pressure and temperature over a period of time. During sintering particles of a powder material are bound together in a mold to a solid part. In selective laser sintering the crucial elements pressure and time are obsolete and the powder particles are only heated for a short period of time. SLS uses the fact that every physical system tends to achieve a condition of minimum energy. In the case of powder the partially melted particles aim to minimize their in comparison to a solid block of material enormous surface area through fusing their outer skins. Like all generative manufacturing processes laser sintering gains the geometrical information out of a 3D CAD model. This model is subdivided into slices or layers of a certain layer thickness. Following this is a revolving process which consists of three basic process steps: recoating, exposure, and lowering of the build platform until the part is finished completely.

Keywords: *selective laser sintering, direct metal laser sintering, sintering parameters, optimization*

INTRODUCTION

The manufacturing industry is always looking for ways to improve production and which is also important - to reduce costs. Traditional manufacturing techniques of materials such as milling or lathing allows to create physical 3D models by removing material with the use of cutting tools. Traditional cutting tools are controlled manually. The rapid development of technology, including CAD / CAM in the 70s allowed for automating manufacturing processes through the use of numerically controlled machine tools. Tools numerically controlled by computer software and modern technologies Milling allowed to shorten production time and efficiency of the process. However, these technologies still have drawbacks due to its working principle [1]. One major disadvantage is the dependence on geometrical complexity. Features such as small holes in the block are difficult to manufacture because of the limitations of the process, and thus interference between the cutting tool and parts. Additionally when the sample size is small, the time for process planning and NC programming can constitute a significant portion of the time needed to manufacture the part. Unlike traditional subtractive machining processes, Rapid Prototyping (RP) (also termed as Layered manufacturing (LM) or Solid Freeform Fabrication (SFF)) is a material additive manufacturing process [2].

Rapid prototyping is performed by incremental forming, which is defined as a set of methods based on *CAD/CAM* technologies in which data collection, processing, and the manufacturing process are assisted by computers [3]. The concept of incremental forming is based on dividing a virtual 3D model into a series of two-dimensional layers, which are then produced in a specialized prototyping device [4]. The term "additive technique" may be used to refer to rapid prototyping and incremental forming, because in contrast to traditional methods, e.g. machining, rapid prototyping does not deal with the production of objects by removal of material, but by building objects layer by layer. There are many methods of incremental forming of physical models.

The RP methods enumerated above are adapted for work in three-dimensional technology and are based on the addition of material in points (discrete or continuous), layers, or surfaces [5]. Elements manufactured by means of incremental technologies are distinguished by high accuracy of shape and dimensions as well as by good surface quality. *RP* methods are diverse due to the essence of their action, the course of the process that is conducted within the framework of a specific method, and the materials used in them [5].

Additive model production technologies allow for the use of more complex CAD geometry. The necessity of assembling a working part from a large amount of small parts is eliminated, and a ready, disassemblable subassembly is obtained in a single process, in one machine pass (not including possible removal of supports and later finishing work). Importantly, these technologies enable engineers to make designs that are not limited by the manufacturing or technological capabilities available at plants [6]. Engineers can now focus on developing new concepts without fear that their idea, in the form of a digital 3D model, will never be realized.

The main advantage of this technology is the relatively high strength of obtained parts as well as the wide range of materials that can be applied. Furthermore, the quality of obtained elements is very high, which is related to the fact that the laser sintering process takes place in a protective atmosphere of inert gas, yielding an elements devoid of admixtures and byproducts of combustion [7].

Rapid prototyping technologies are entering their third decade of commercial use. Over this time, many distinct changes have taken place, leading to improvements in the scope of surface quality, dimensional accuracy, mechanical properties, applicability, and to reduction of the manufacturing costs of elements produced using these methods. Achievement of high accuracy of designed models is a very significant problem [8]. It is linked to the possession of a laser with the appropriate parameters. Considering the complexity of individual machines, their maintenance and operation may be linked to additional activities, maintenance, or operating methods. The applied software and its version is also an important factor. This is because the software allows for the application of advanced settings of the process's technological parameters - and thus, greater versatility of applications. Many new RP technologies have been introduced and the application of RP technologies has become wider and wider. As one of the rapid prototyping processes, the selective laser sintering (SLS) technique builds prototype parts by depositing and melting powder material layer by layer.

Although it is a relatively new technology, the RP based SLS process challenges the traditional material removal processes.

DMLS CHARACTERISTICS OF THE PROCESS

The purpose of the technology is to produce RP three-dimensional models directly from the metal powder. SLS technology is one of the RP methods, by which we are able to produce metal prototypes by sintering the powder particles [5]. The basic step in the process of rapid prototyping is to define dimensional model of the object as a 3D-CAD. It is then processed processes the numeric character data set suitable for RP systems. The original 3-D CAD model is sliced into a set of parallel layers filled by hatch lines. The layer information is then used to drive the machine directly. There are normally three sub-stages in the data preparation stage, and these are described in the following sub-sections [2]:

1. Build the CAD model
2. Triangulation of the object
3. Transition of 3-D models into 2-D layer models

There are two different metal sintering methods proposed based on SLS technologies: indirect laser sintering and direct laser sintering. Indirect laser sintering does not have wide industrial applications due to its relatively low-density parts and the necessity of postprocessing. Direct Metal Laser Sintering (DMLS) is a new laser-based Rapid Tooling and Manufacturing (RTM) process developed jointly by the Rapid Product Innovations and EOS GmbH.

Indirect selective laser sintering utilizes metallic powder coated with a polymer 5μm in thickness. The laser beam sinters the polymer layer, and metallic powder grains remain unchanged. An object obtained using this method is characterized by low strength properties and high porosity (even above 50%), which is why it is necessary to subject it to further thermal treatment [9].

Thermal treatment is divided into two stages: polymer removal and infiltration. High temperature causes evaporation of the polymer. A further increase in temperature leads to the formation of necks between metal particles (sintering). The next step is infiltration, which is based on filling pores remaining after polymer evaporation with metal of a low melting point or on further sintering until full density is achieved [10,11]. In addition, if pores are filled with a different metal, infiltration allows for the production of composites with desired properties [12].

In the case of direct laser sintering (DSLS), a high-power laser beam acting on a metallic powder substrate leads to its direct sintering [13]. An advantage of this type of selective laser sintering is that it eliminates costly and time-consuming thermal treatment. DSLS technology makes it possible to apply a mixture of different powders with different properties. This enables sintering of specialized materials with good and unique properties: cermets or alloys based on cobalt, nickel, and titanium [14]. These materials have strictly defined applications, which is linked to the high temperatures employed during the process, stresses, and rigorous conditions having an influence on oxidation or corrosion [15].

Sintering is a high-temperature consolidation process (thermal consolidation) to which loosely spread powder is subjected, and as a result, the system's free enthalpy is reduced as temperature is increased, causing reduction of porosity and an increase of material density [16,17]. These are macroscopic manifestations of sintering arising from the changes occurring inside the sinter. In the sintering process, mechanical connections between powder particles are transformed into metallic bonds of greater strength. When analyzing the theoretical aspects of the sintering process, driving forces and matter transport mechanisms must be accounted for [18,19,20].

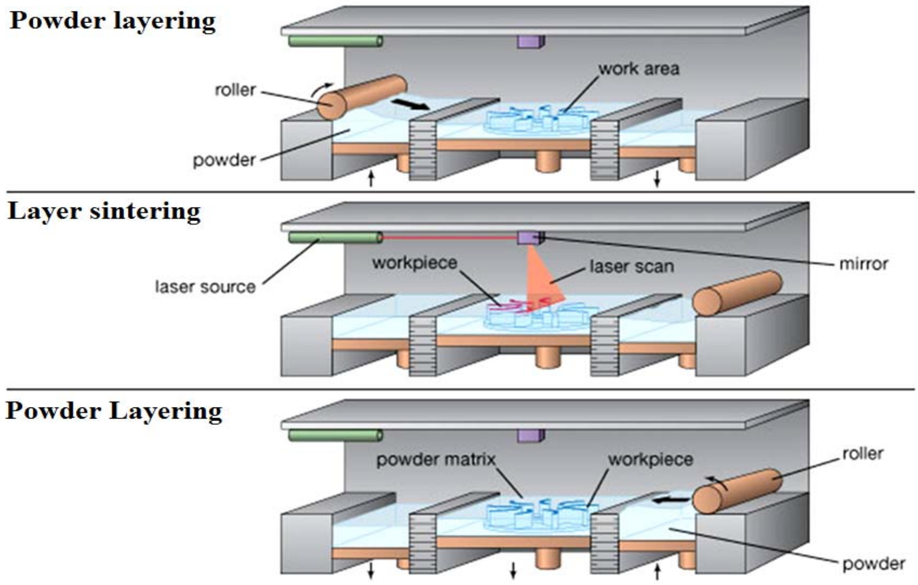

Fig. 1. DMLS process [20]

PROCESS PARAMETERS

Changing the sintering process parameters affect the quality. The most important parameters responsible for the quality of the produced element include: dimensional accuracy, mechanical strength, processing time, surface roughness, cost, part orientation, hatch space, scan path pattern, offset and scaling, layer thickness, scan speed and laser power.

Among these parameters, one of the most important is the scanning path. There are two paths (two patterns) scanning - spiral consisting of a number of oval contour having different offset values. The second method is a parallel path along the predetermined direction. In the SLS process, a focused laser beam is delivered onto the powder to heat and melt it. The material is combined together and the model is built layer by layer. But, what is important and necessary to remember about the fact that the hot part cools down and shrinkage is inevitable. In addition, the finite width of the laser beam causes material to fuse outside the desired part boundaries. In order to build parts with high accuracy, it is necessary to scale the 2D layer files to compensate shrinkage and offset 2D layer file to compensate the beam diameter. So far, some different offset methods have been used such as dihedral offset, normal offset and constant offset. The dihedral offset has been adopted in the system because the dihedral offset method is more accurate than the others [22].

Layer thickness has a close inverse relationship with the total processing time. It is the most important factor when the processing time is concerned more than other resulting properties. The strength of the part, which is primarily a function of fractional density has a reverse trend with layer thickness [23]. Thickness also has a close relationship with the surface quality. The staircase error that influences the surface quality is unavoidable when using the finite layer thickness to laminate parts.

Before the fabrication, two important process parameters, scan speed and laser power, need to be decided based on the laser system and powder material properties. The presence of the liquid phase results in rapid sintering since mass transport can occur by liquid flow and particle rearrangement [24]. The energy needed to melt the metallic powder is much more than that needed to melt polymer powder, which is often used in the SLS process. Therefore, high laser power and slow scan speed are normally used in the metal sintering. Normally, a higher laser power and slower scan speed also bring higher part strength because more energy is absorbed by the loose metallic powder. It results in a higher density in the built part. But oversintering will occur when the energy is too high. The resulting properties will then decrease sharply. The higher laser energy will bring a larger fused zone each time but will affect the part accuracy. In general, the sintering layer surface roughness will increase with increasing laser scan speed [25]. Therefore, it is important to make a trade-off between the scan speed and laser power setting.

THERMAL MODELLING

As a rapid liquid sintering process, densification is performed at a high temperature to produce transient liquid sintering of the part to near full density with desired shape and dimensional tolerances [13]. The liquid phase exist time and the wetting ability are critical to the final sintering properties. Temperature is believed the most important factor for the liquid phase exist time and the wetting ability. Increasing the sintering temperature leads to a larger amount of liquid phase formed and with a low viscosity of the liquid flowing. Extending the sintering time will cause more sufficient flow of the liquid. Hence, the history of the sintering temperature is critical for the final sintering quality [21]. When the material system is decided, the sintered powder temperature history and the temperature distribution in the whole powder bed are determined by the energy input and the rate of heat losing. During the sintering process, the powder temperature will increase sharply when the laser scans them by absorbing the energy from laser [22]. Besides the material properties, the laser energy absorbed is controlled by two important process parameters: scan speed and laser power. When the laser beam passes the powder, the temperature will decrease due to the heat loss through the powder bed and atmosphere environment. The heat transfers to the atmosphere mainly by convection and radiation at the surface of the powder Bed as well as conduction into the surrounding powder bed. The loss of the heat is closely related with the whole powder bed temperature distribution decided by hatch space, layer thickness, laser power and scan speed [25].

To better understand the sintering mechanism with the further effect on the sintering quality, several researchers have attempted to build a reasonable thermal model to denote the heat transfer during the SLS process. Based on that thermal model, numerical modeling can be created to investigate the temperature field of powder bed. Thermal function is built by considering the energy input from the laser and loss by heat transfer. In the earlier stage, the sintering material is mainly focused on amorphous powders such as polycarbonate bonded by fluid flow that does not incur a phase change hence with a near zero latent heat. Works reported analyzed the thermal models with the sintering of amorphous powder. In their models, the heat source input from laser sintering is calculated as a function of the laser position and the power distribution of the laser beam [26-28]. Heat losses at the surface are considered as results of conduction, radiation and convection. Later works focus on the

crystalline polymer such as nylon are reported [29-30]. Because the crystalline polymer has a low melting temperature, the effect of latent heat is considered in the thermal model.
For the two-phase metallic powder system, only the component with low-melting-point melts to infiltrate and wet the high-melting-point solid powder. Unlike the single-phase sintering, the heat transfer becomes more complicate. In this situation, the melting and resolidification phenomena accompanying with releasing very large latent heat have a significant effect on the thermal distribution of the powder bed. Besides the latent heat, the movement of the two different components during the sintering also has a significant effect on the whole thermal process. Some of the authors proposed the use of powder mixture containing two powders with significantly different melting point in which only the low melting point powder melts [29]. But the effect of both liquid and solid velocities on the heat transfer is ignored. The liquid flow driven by capillary and gravity forces and the solid particle velocity induced by shrinkage of the powder bed are taken into account in Zhang's model [31].

PART ACCURACY

The ability of a Solid Freeform Fabrication (SFF) process to produce accurately shaped geometry is critical to its overall acceptance in the market place [22]. To achieve an accurately built part is a time-consuming and complicated task because many factors can affect the final dimensional accuracy. Some researchers have focused their attentions on one or several of the following factors.
Rapid prototyping of 3-D models are performed by generating and stacking in two dimensional (2-D) cross sections of uniform thickness. In rapid prototyping, the fabricated part has a quantification error when the height is not a multiple of the finite layer thickness. Hence, adaptive slicing algorithms [32,33] been developed to reduce these kinds of slicing errors. To process the 2-D layer data, 3-D model is first converted to a faceted model (in STL format). This incurs another pre-processing error during the tessellation of the faceted model when a sufficiently high tessellation resolution is used to meet the accuracy requirement. Some proposals using other data formats such as constructive solid geometry (CSG) and NURBS-based representations instead of the STL representation have been proposed [33-36].
Machine errors can be measured, appropriately calibrated and compensated. The effect of the overall system errors can be controlled to a reasonable scale. Besides the error factors mentioned above, the final part dimensions are not uniforming practice even when two processing environments are similar. It occurs due to the small fluctuation of process environment [37,38].
The dimensional errors arising from the material processing are the most complicated factors and have attracted much attention in RP research. In the SLS process, the temperature of part or all of the powder is raised above its softening (such as for plastic powder) or melting (such as for metallic powder) temperature to bond and solidify the particles during the laser sintering process. After the process, the sintered part shrinks as it cools. To compensate the effect of material shrinkage, the 2D-layer model needs to be scaled first. Besides these, an offset of the 2D-model is processed to compensate the effect of finite diameter of the laser beam spot. A simple method is to use a constant offset factor and scaling factor during the sintering process [38]. Percentage shrinkages vary with different geometric shapes causing different accuracy errors in the whole part. But the effect from the different geometric shapes is however not considered in the linear-fitting model.

It is important to effectively analyze and compensate the effect of different geometric shapes to improve the dimensional accuracy of the entire part. It was obtained experimental data for measuring shrinkage values of many different geometric shapes with a fixed parameter setting and then applied different shrinkage compensation factors to the CAD model for each section of a part [39]. It is a tedious task especially for complex geometries that need plenty of experimental data. The results are also difficult to generalize when the process condition changes. The difficulty of using a relatively simplified method to denote the shape character based on the SLS process is another problem. The geometric reasoning becomes a very difficult task in the case of complex geometries.

The final part accuracy is mainly influenced by the shrinkage of sintered material. The difference in the length of hatch lines filled in the different 2-D layered geometry causes uneven shrinkage rate. If the shrinkage rate is not uniform, the compensations become hard to implement. Additionally, the material warpage and distortion related to the inhomogeneous material shrinkage are other serious problems in the laser sintering process. Currently, none of the technologies has the capability to effectively avoid or control the heterogeneous effect caused by the variation of geometry shape.

Part mechanical property is an important resulting property of concern to users especially if they want to build functional prototypes by RP systems. Research works have been done on the effect of different process parameters on part mechanical properties with different RP processes [40-44].

For parts built by selective laser sintering (SLS), some models are created based on the understanding of the laser energy delivery system. In 1993 physical model of the sintering process that relates the sintering depth and laser control parameters has been constructs a. In this model, the Andrew number (An) is proportional to the part strength and is shown to be a combination of the scanner parameter to yield:

$$A_n = \frac{Laser\ power}{Beam\ speed\ x\ Hatch\ space} \qquad (1)$$

However, the equation achieved is based on the amount of the energy delivered to the surface where the energy lost though heat transfer is not considered. In 1997 developed the model by considering the effect of the period of time the powder cools [45,46]. The change of vector length results in changes in the delay period between successive exposures. Besides that, the amount of sintering that occurs and the final part strength are expected to be influenced by the number of laser exposures owing to an increase in the amount of overlap. The new model relates the number of exposures and the time of the delay period to the resulting part strength. By using regression models based on a batch or experimental results, the new model is given as:

$$Strength = K_1 \cdot A_n - K_2 \cdot Scan\ Rate \qquad (2)$$

where the coefficient factors *K1* and *K2* can be calculated through statistic method based on the experimental results. Although the model considers the effect of heat transfer between scan lines, it is still hard to predict the strength in the geometry-complicated part because the time period between scan lines varied with the change of geometry shapes in each 2-D layer.

Some works try to understand the relationship between different parameters and the mechanical strength through experimental methods on different material system. It was

discussed the effect of vector length, bed temperature, polymer melt index and initial binder content on part strength and density by madding some test bars [41]. Gibson and Shi (1997) investigated the influence of scan size, scan spacing, laser power, hatch direction and orientation on the mechanical properties of SLS process [47].
The length of the hatch line is an important factor found to be significant to affect the quality of the final part according to earlier studies [48]. As the hatch length increases, the time delay between energy pulses increases thereby lengthening the cooling time and reducing over-sintering [41]. However, a short hatch length and its corresponding short scanning time results in heterogeneity in the material properties of the part. This unevenness affects the quality and mechanical strength of the parts built. Although many studies have been reported earlier, little work was done with a systemic research.
Besides the effect of the sintering process in each 2-D layer, the sintering part is not isotropy because of the different build direction (orientation). Subramanian et al. (1994) discussed the anisotropy of green strength due to the selection of different orientations [40]. Then David and Richard studied the relationship between the strength and part orientation by using the Tasi-Wu interactive tensor polynomial model [42,49].
As an important issue affecting the part quality, surface roughness is most important when prototyping is used for casting. Two different types of surfaces are formed when the 3-D physical model is created. The first type of surface is created along the sintering direction by a continued accumulation of the 2-D contour of each layer and defined as contour accumulation surface in this study. Ideally, this type of surface is smooth when the thickness of each layer is small enough. But because the existence of height of each layer, the surface smoothness when created initially in a CAD system will be broken. On sloping or curved surfaces, a stair-case error will appear. The most popular method to evaluate this stair-case effect is using the cusp height. It is defined as the maximum distance between the CAD model and the built layer measured along the surface normal.
The negative stair-case effect is directly related to the layer thickness. Two methods are widely applied to minimize the stair-case effect in relation to the process parameter. The first one used the adaptive slicing method to adjust the thickness of each layer based on different geometrical features of the model [34,50-52]. To reduce the staircase effect, the layer thickness should be reduced, but this will increase the part building time. The solution of this problem is to adaptively slice the model, so as to achieve a balance between the surface qualities and build efficiency. Another method is the orientation optimization method [53-55]. By optimizing an appropriate orientation, the specified accuracy can be attained with a minimized processing time. In some studies these two methods are combined together.
Processing time is an important factor affecting the product cost. Several process parameters such as thickness, scanning speed, the orientation and hatch distance can affect the build time of the prototype significantly. Unlike the other properties, for processing time, there is normally a clear quantitative relationship with the parameters, so that a direct mapping function can be deduced based on different processes. There are two methods to estimate the processing time: based on equations derived as astatistic function of the total volume of the parts to be built [56] or a function of the total laser scan distance that the laser travels [57].

MULTI-OBJECTIVE PARAMETER OPTIMIZATION SYSTEM

The developed thermal model provides a strong theoretical support for understanding of the sintering mechanism. But it is still hard to directly apply to predict the resulting properties of the sintering part. To build the model, some assumptions are necessary to simplify the model. Many factors including the process parameters and material properties bring different effects on the thermal model and seriously limited the application of these models. In the current research, experimental methods are adopted to build the relationship between the process parameters and resulting properties directly. After the mapping relationship is built with the analysis of experimental result data, the parameter optimization becomes possible. Many goals such as dimension accuracy, mechanical strength, processing time, and surface roughness are the primary concerns to the users. Some of the important process parameters together could affect the resulting properties significantly. Very often, these goals do not necessarily result in a similar trend as the change in the process parameters. Inevitably, a fixed set of parameter values that can achieve the best outcome even for two of all desired properties inevitably do not exist [58].

Traditionally, the way to solve this is to make a trade-off among these goals. These guidelines are intended in improving the strength and accuracy of the parts made by the FDM machine. Through analysis of the energy delivered to the powder medium, Williams and Deckard (1998), studied the effects of selected parameters on the SLS process response [59]. A model based on the physical principles involved, including sintering, heat transfer and thermal gradation was presented. The basis for the process is D-optimality criterion applied to a series of factorial experiments that capture empirically the relationship between the process parameters and part quality measures [60].

The way to solve this by making a trade-off among these goals may not be good enough under many different requirements requested by the customers. In fact, in different applications, the users are often more concerned with some of the resulting properties but ignore the rest. For example, if the prototype part is created mainly for design review, processing time and surface roughness will be given more attention; if it is for fit and assembly verification, the dimensional accuracy is more important; and if for limited functional testing, the mechanical strength could be the main property concerned. A good scenario is auto-selecting the process parameter setting to satisfy the various requirements for different users. This could make the RP applications more agile and acceptable [61].

There are several process parameters that significantly affect the different resulting properties. It is important to build a suitable model by creating a proper mapping between the parameters and properties. However, there still does not exist an intelligent system that can help the user select the correct process parameters for DMLS process based on their applications.

RESEARCH SCOPE

Currently, rapid prototyping has taken its place alongside CAD software, CNC milling, injection molding and electrical-discharge machining as an indispensable tool in the process of design and manufacturing the world’s product [62]. As one of the important technologies that have the potential to build metallic parts directly, direct metal laser sintering technology is an important research field to carry RP technologies forward into the realm of custom manufacturing.

Although DMLS technology can bring about great benefits, the sintered part quality is still not good enough to produce an accurate and dense part. Improvement in the final sintering quality is widely expected in industry. There is still much research work to improve the performance of RP. The research scope proposed in this thesis focuses on the DMLS process

parameter issues. Based on the previous work, an experimental DMLS machine was developed for research on the process [63].
Process parameters are the key factors to control the final properties effectively. As discussed earlier, certain process parameters determine efficiency, economy and quality of the whole sintering process. Therefore, correct setting and control of these parameters is a primary requirement for successful application. Based on this, the research proposed in this thesis is focused on optimizing the key controllable parameters to achieve better performance of the DMLS process. Specifically, this research focuses on the following issues [64]:

1. Analyze the effect of different process parameters on the resulting properties. Several experiments are conducted for this analysis.
2. Develop an intelligent system based on the Feed-forward Neural Network (NN) with backpropagation (BP) learning algorithm to predict the resulting properties of the laser-sintered metallic parts built by different process parameter settings. Compared with traditional approaches, the NN approach can provide a good mapping between inputs and outputs without the aforementioned assumptions and simplifications. Moreover, the NN model is easier to build. These advantages make it a powerful tool to predict complicated process relationships. It is invaluable for users to search for some specific properties and the system automatically determines the most suitable parameter setting to achieve desired outcome with good accuracy.
3. Measure the quantitative relationship between material heterogeneous and anisotropic properties, and the part quality by designing an experimental method. Material anisotropic and heterogeneous properties cause the sintering quality not uniform and distortion and warpage of the sintered part may occur in such case. In this study, the factors affecting the material heterogeneity and anisotropy are analyzed. With the understanding of the effect of material heterogeneity and anisotropy on the final quality, there can be further control of this effect.
4. Control and minimize the effect due to the heterogeneity caused by the different geometric shapes of each layer. Two methods are presented: i) a hatch direction optimization method based on a proposed genetic algorithm (GA) approach to reduce the short hatch-lines, and hence reducing its negative effect. Because GA does notrequire derivative information or other auxiliary knowledge and only the objective function and corresponding fitness levels that influence the search (Zalzala and Fleming, 1997), it is suitable for use to solve this optimization problem. ii) a speed compensation (SC) algorithm developed to give more homogeneity properties for sections with hatch lines of different lengths. By changing the sintering speed based on the length of the hatch line, the material property can be more homogeneous. With the optimization methods, the material can be made more homogeneous and the properties become more controllable.

CONCLUSION

Direct metal laser sintering is designed to manufacture small batches of relatively accurate and structurally sound 3-D metallic parts. Some process parameters have significant influence on the final properties of the part [65]. To achieve the desired properties of the final part, the appropriate process parameters must be set. For this purpose, many researchers aimed to improve these properties by studying the effect of process parameters on them [66]. The literature review indicates that much research work has been attempted to improve the sintering quality by optimizing one or several important process parameters. However, the relationship between the process parameters and the resulting properties has not been totally understood especially for the metallic materials. To further improve the sintering quality, more research work should be done to satisfy the requirements from users and manufacturers.

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