DEVELOPMENT OF F[illegible] SPEED MACHINING USING SMALL BALL END MILLING PROCESSES

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ABSTRACT

This thesis describes the development of 2D and 3D finite element (FE) models for the high speed machining on laser sintered material, LSMEρ9. The work employed finite element method (FEM) with the application of Updated Lagrangian Formulation. Mild steel, AISI1055 was used as a comparison. Finite element simulation results of cutting force show errors of 10%, compared with experimental results when shear friction factor, m 0.8 was applied. The cutting force shows increasing values when the radial depth of cut increases for both types of materials due to chip removal rate increases. However, the cutting force decreases when the cutting speed increases due to the decreases of chip thickness and less contact time between tool and chip. The cutting temperature increases when the cutting speed increases due to increasing in cutting energy. Cutting force for laser sintered material, LSMEρ9 is lower than mild steel, AISI1055 due to its lower young modulus while its cutting temperature is higher than AISI1055 due to its lower thermal conductivity. Extended studies were done for ball end mill with the diameter equal or less than 2mm. The predicted cutting temperature for ball end mills with diameter 2 mm and less shows big error compared with the experimental results due to the size effect of the ball end mill was neglected in the simulation. The heat capacity of the small size of the ball end mill is considerably low, thus the end mill could suffer excessive increases of cutting temperature. The large ratio of feed rate per tool radius (>0.1) could lead to increases of tool wear rate, thus worsen the heat capacity of small ball end mill. The study on effect of tool wear evolution during machining on the cutting temperature was done. In the study, cutting temperature increases when flank wear of the tool increases, while prolong machining increased the cutting temperature

gradient critically. Increasing temperature during machining could affect the surface integrity of the workpiece and cutting tool, lowered the tool life and quality of the manufactured products.

ABSTRAK

Tesis ini menerangkan tentang penghasilan model 2D dan 3D unsur terhingga (FE) untuk pemesinan berkelajuan tinggi terhadap bahan sinteran laser. Di dalam kajian ini, kaedah unsur terhingga (FEM) digunakan untuk mensimulasikan kaedah-kaedah eksperimen dengan mengaplikasikan formulasi Lagrangian yang dikemaskini. Keluli lembut, AISI1055 digunakan sebagai perbandingan. Berdasarkan keputusan simulasi yang telah dijalankan, daya pemotongan menunjukkan ralat piawai relatif sebanyak 10%, apabila dibanding dengan keputusan eksperimen ketika pekali geseran ricih, 0.8 digunakan. Daya pemotongan menunjukkan peningkatan nilai apabila kedalaman jejarian ditingkatkan bagi kedua-dua jenis bahan kerana peningkatan kadar penyingkiran serpihan. Walau bagaimanapun, daya pemotongan menunjukkan penurunan nilai apabila kelajuan pemotongan ditingkatkan kerana pembentukan serpihan yang nipis dan pengurangan masa sentuhan antara mata alat pemotong dan serpihan yang mengurangkan daya geseran semasa permesinan. Suhu pemotongan bertambah apabila kelajuan pemotongan ditingkatkan disebabkan oleh peningkatan tenaga pemotongan. Keputusan menunjukkan daya pemotongan bahan sinteran laser adalah lebih rendah dibandingkan dengan daya pemotongan, AISI1055 kerana modulus Young yang rendah tetapi suhu pemotongan bagi bahan sinteran laser adalah lebih tinggi kerana kekonduksian haba yang lebih rendah. Lanjutan kajian telah dijalankan bagi alat pemotong berdiameter 2mm dan kurang. Berdasarkan keputusan simulasi, ralat suhu

yang besar diperolehi apabila dibandingkan dengan keputusan eksperimen kerana pengabaian kesan saiz alat pemotong ketika simulasi dijalankan. Muatan haba alat pemotong bersaiz kecil adalah agak rendah menyebabkan alat pemotong mengalami peningkatan suhu permotongan yang berlebihan. Nisbah kadar suapan per jejari alat pemotong yang besar (>0.1) mampu meningkatkan kadar kehausan mata pemotong, sekaligus merendahkan lagi muatan haba alat pemotong. Satu kajian mengenai kesan penumpulan mata alat pemotong semasa pemesinan terhadap suhu pemotongan telah dijalankan. Berdasarkan kajian tersebut, suhu pemotongan meningkat apabila haus mata alat pemotong bertambah, manakala memanjangkan masa pemesinan mampu meningkatkan kadar kenaikan suhu pemotongan dengan kritikal. Peningkatan suhu pemesinan boleh menjejaskan keutuhan permukaan bahan kerja dan alat pemotong yang mampu menurunkan jangka hayat alat pemotong dan kualiti produk yang dihasilkan.

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NOMENCLATURE

A_d Axial Depth of cut (mm)

α Rake angel (°)

a Cooling ratio

β Friction angle (°)

b Cutting width (mm)

γ Clearance angle (°)

δ Cooling time (s)

F Friction force along the rake face (N)

F_c Cutting Force (N)

F_N Normal Force (N)

F_s Shear Force (N)

F_t Thrust Force (N)

F_v Cutting force (N)

f Feed rate (mm/tooth)

h Contact length (mm)

k Normal stress (MPa)

l Length of cut (mm)

l_c Chip length (mm)

m Shear friction factor

μ Coulomb friction factor

Q_r Heat Generation rate (W)

q Heat Flux (W/m^2)

ε Shear strain

$\dot{\varepsilon}$ Strain rate(s^{-1})

F_R Friction force (N)

R Tool radius (mm)

R_{ef} Tool effective radius (mm)

R_d Radial Depth of cut (mm)

r Chip compression ratio

T_ψ Temperature at degree (°C)

T_0 Temperature at 0 degree (°C)

T_r Room Temperature (°C)

τ Flow stress (MPa)

t Undeformed chip thickness (mm)

t_c Chip thickness (mm)

θ Shear angle (°)

U_s Shearing energy (W)

v_s Shearing speed (m/s)

v_c Chip velocity (m/s)

v_w Cutting speed (m/s)

W_c Machining work done (W)

Chapter 1

INTRODUCTION

1.1 Introduction

Injection moulding is one of the most flexible and prominent operations for mass production of complex plastic parts with excellent dimensional tolerance. In the conventional mould manufacturing, the injection mould is made from hardened steel using subtractive processes such as high speed machining (HSM) (Dewes et. al, 1997) and electro discharge machining (EDM) (King et. al, 2003). However, these processes are time-consuming. Thus, they are not economic due to the time to market has become the crucial factor for success in the consumer product marketplace. Moreover, in making a mould having a deep rib, the declination at the cutting edge is the main factor behind various negative effects such as chatter, wobble and impact loading. This factor could cause poor dimensional accuracy, which is adverse in making a precise mould. Hence, it is important to keep this deflection at the minimum. The simplest method to control the tool deflection is by reducing the tool length and maintains high material removal rates. Therefore, this conventional mould manufacturing is impractical to make the complicated injection mould having a deep rib.

Stereolithography (SL) practices in mould manufacturing has reduced mould production time and cost (Figure 1.1). Additionally, a mould having a deep rib can also be created. However, life span of the mould produced from SL is short due to its low flexural strength (Ramada et. al, 2007).

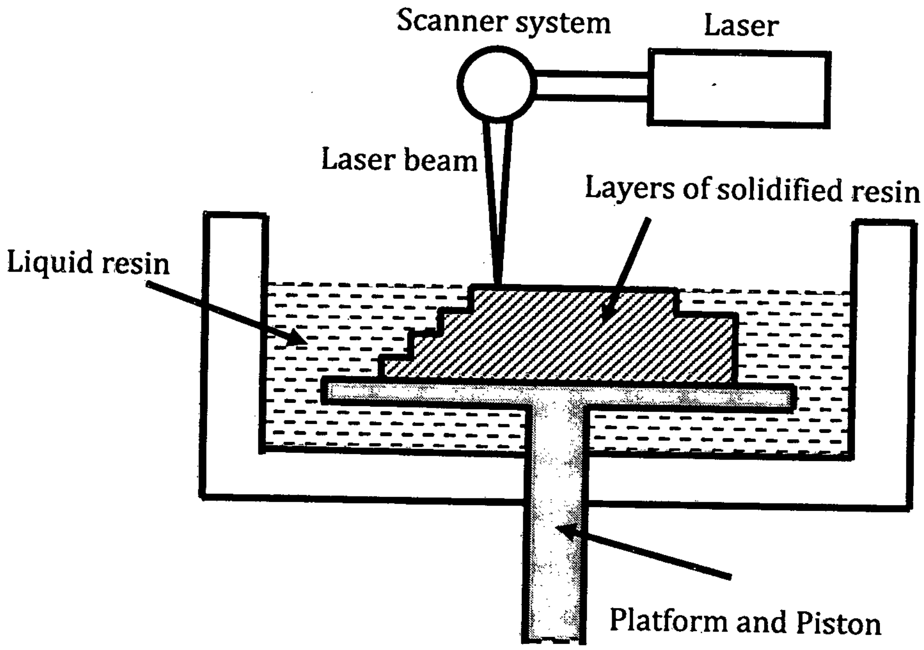

Figure 1.1: Stereolithography (SL) (Yassin, 2009)

Selective Laser Sintering (SLS) application in making three dimensional parts by sintering metal powder with laser beam could greatly reduce the manufacturing time and increase the life span of the mould (Figure 1.2). However, the resulting part offers poor surface roughness and limited accuracy.

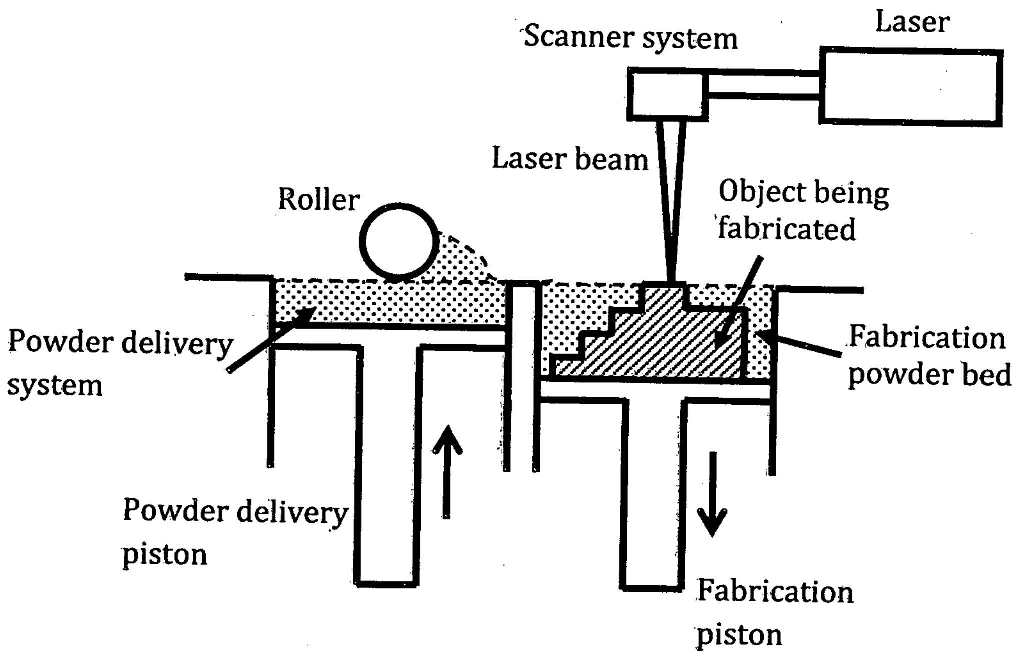

Figure 1.2: Selective Laser Sintering (SLS) (Yassin, 2009)

1.1.1 Milling combined laser sintered system

Milling-combined laser sintering system (MLSS) is a rapid tooling machine that integrates laser sintering of fine metallic powder and high speed milling. It has been developed to overcome deficiencies in mould making by the conventional method.

In MLSS, small diameter ball end mill is employed to machine the mould having a complicated feature due to the capability of ball end milling process in machining free-form surfaces (Abe, 2008). Therefore, the dimensional accuracy is improved plus with the additional ability to make deep rib onto the mould. Furthermore, a cooling channel such as spiral holes along the mould profile can be created easily, which is difficult in the conventional machining process (Abe, 2008).

It is reported that in MLSS, the apparatus for laser sintering part consists of a continuous wave Yb:Fiber laser (λ = 1.07 μm) with a maximum output power of 200 W, a laser spot's diameter of 94 μm and a maximum laser scanning speed of 10,000 mm/s (Yassin, 2009). Furthermore, the apparatus for the high speed milling part consists of a spindle with a maximum rotational speed of 50,000 rpm and a highest feed speed of 1,000 mm/s.

There are two alternating processes that occur in MLSS, particularly layer profile forming by laser sintering and surface finishing by high speed milling. Figure 1.3 illustrates the concept of the MLSS. The process of MLSS can be summarized as follows (Yassin, 2009);

1. A 3-D model is designed using CAD and the 3D model is divided into 50 μm thickness of sliced layers. Then, this model will be input into the MLSS processor unit. Prior to the laser sintering process, a sandblasted steel base plate is placed on the machine platform.
2. A predetermined layer thickness of 50 μm of loose metallic powder is spread on the base plate using a recoating blade. Consecutively, the laser beam is irradiated to the surface of a layer of loose metallic powder to produce a layer-wise profile according to the CAD data, see Figure 1.3(a).
3. After forming a few layers of laser-sintered material, the milling process is executed at the periphery surface as shown in Figure 1.3(b). The sintering and milling at the periphery surface are repeated whereas top surface is not cut after all layers are sintered. In order to increase the accuracy of the mould, the periphery surface of the mould is cut in two steps, namely rough milling and finish milling as shown in Figure 1.3(c).

The laser sintering and cutting processes are performed in the nitrogen atmosphere at room temperature to prevent oxidization (Yassin, 2009).

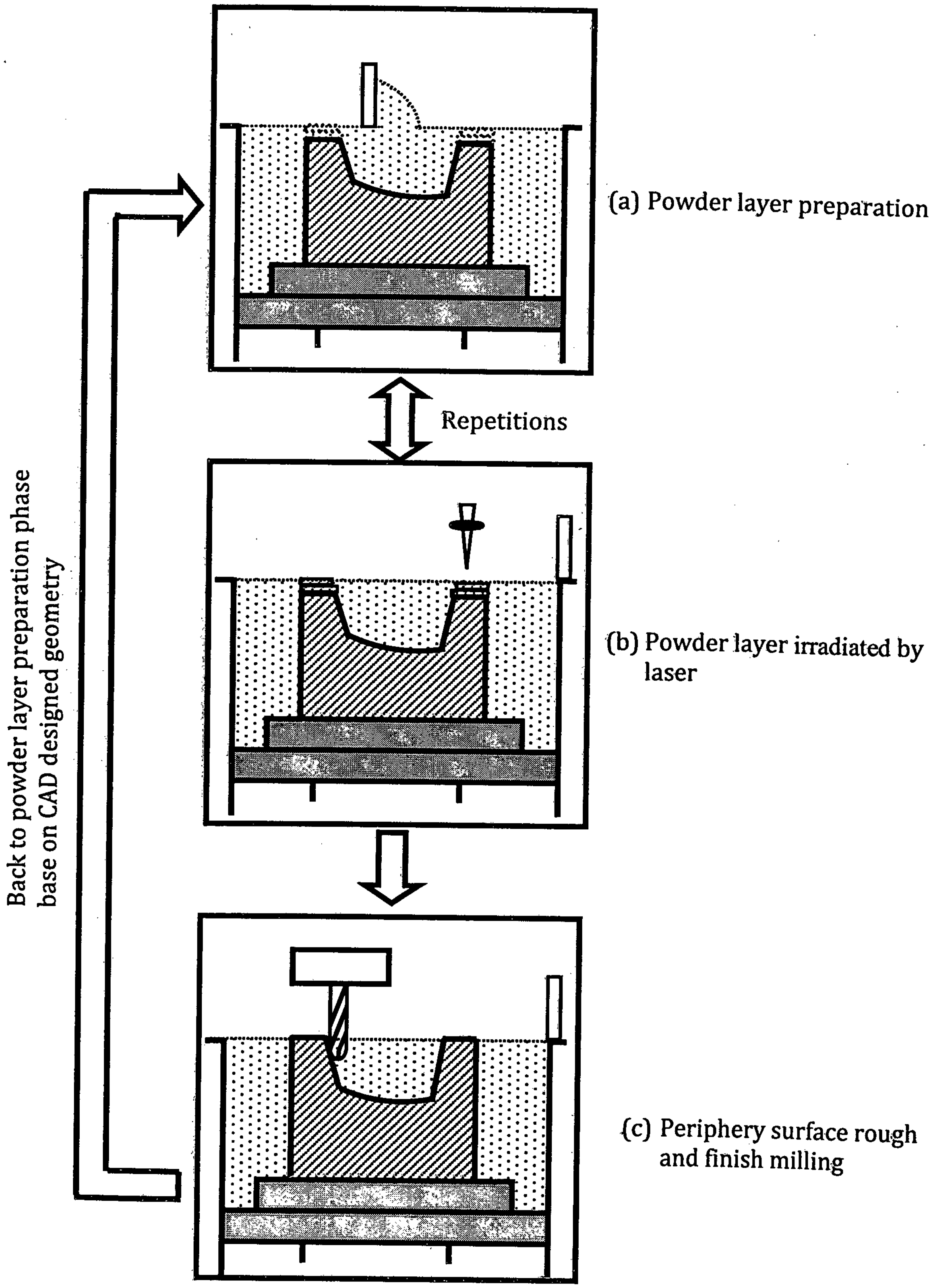

Figure 1.3: Milling Combine Laser Sintered System (MLSS) (Yassin, 2009)

The dimensional accuracy and surface roughness of the mould manufactured by MLSS is almost equal with the one made by a machining centre. There are still less attention has been paid to the machinability study of laser sintered material (Abe et. al, 2008, Yassin, 2009). Therefore, there is a need to study this problem, if we want to take advantage of MLSS as a new invention in making complicated injection mould efficiently.

1.1.2 Application of finite element method (FEM) in solving machining problems

In recent years, application of finite element method (FEM) has become renowned in simulating high speed machining. Finite element method (FEM) is a numerical method that separates a problem into smaller regions. It is proven useful in saving the research cost and time. Plus, it is capable to forecast effects of cutting parameter such as cutting force and cutting edge temperature (Abukhshim et al., 2006; Filice et al., 2007)

In machining, estimated cutting forces and temperatures can be applied in tool wear studies to obtain the optimum cutting parameters such as cutting speed, cutting depth, etc. With these conditions, cutting tool can be optimized for its productivity, less experimental trial and expensive costs on tool can be decreased (Filice et al. 2007).

Finite element analysis in machining processes has been widely developed by researchers. The simplest model for these analyses is the 2D orthogonal cutting. In this model, cutting edge moves perpendicular to the relative motion between cutting tool and workpiece to remove unwanted material from the workpiece with constant uncut chip thickness. Additionally, this model is suitable to simulate the turning processes where uncut chip thickness equal to the feed per tooth, which is constant. However, in milling processes, uncut chip thickness modulated depends on not only radial depth, cutting tool diameter and cutting feed, but also radial position which is variable (Ozel et al., 2006; Filice et al., 2008)

The earlier researchers such as Usui and Shirakashi (1982) developed 2D orthogonal cutting to obtain steady-state cutting with the application of iterative convergence method in FEM. While Strenkowski and Carroll (1985) developed numerical model using updated Lagrangian code where problems can be solved without a preformed surface.

Recent 2D model developed by Özel (2006) and Filice (2008), applied friction condition in obtaining more realistic data. J.P. Davim (2009) studied plastic strain and plastic strain rate in machining AISI1045 FEM simulation.

1.2 Problem Statements

The invention of MLSS has reduced the mould manufacturing time about 62% as compared with the conventional mould manufacturing. Furthermore, the moulding accuracy improved by 20% as compared with the conventional steel mould with the application of small ball end mill (Yassin, 2009).

Laser-sintered material (LSM) is a new type alloy that being used in mould making, consist of chrome molybdenum steel, nickel and copper powder compositions. The metallic powder composition is sintered by laser power of 9 (J/s) that is enough for powder to be completely melted. Additionally, the laser-sintered material is porous, with low young modulus and thermal conductivity, but high material hardness (Yassin, 2009).

Laser-sintered material can be considered as a material that is difficult to be machined due to its porosity and inhomogeneous in terms of its mechanical and thermal properties. Moreover, the cutting process in MLSS must be done in dry condition to avoid contamination by cutting fluid. Plus, machining process takes about 30% from the total production time in making a mould. However, the machinability of laser-sintered material is still not well understood (Yassin, 2009).

Therefore, to take advantage of MLSS in making a complicated injection mould in shorter time, low-cost and high accuracy, finite-element analysis is needed to improve the understanding for the cutting characteristic of laser-sintered material and cutting performance of small ball end milling.

Nevertheless, this study will enhance the understanding on high speed machining laser-sintered materials for producing high quality and precision mould efficiently.

1.3 Objective Of The Study

The major goal is to study the laser sintered material machinability and cutting performance of small ball end milling using finite element method. The following objectives have been set in order to complete this major goal:

a) To develop finite element models for small ball end milling processes using commercially available finite element analysis software (ANSYS, DEFORM3D, etc.)

b) To simulate the end milling processes for laser sintered material and mild steel using the developed models.

c) To validate the simulation results with the experimental results and analyze the errors of the models.

d) To study the effect of cutting parameter and diameter of ball end mill on cutting performance of small ball end mill and cutting characteristic of laser-sintered materials.

1.4 Significance Of The Study

Application of finite element method is important research ability in improving manufacturing and industrial capability, especially in mould making. This research is one of the efforts in extending knowledge for computer-aided manufacturing while reducing the cost in research and industry. In addition, the models and methods in this research can be employed at any manufacturing industry, especially in studying new materials and obtaining optimum manufacturing conditions.

Nevertheless, this study can help in future development of new industrial and manufacturing engineering of mould making in Malaysia.

1.5 Layout Of The Thesis

In this introduction section, an overview of the task involved in accomplishing the main objectives of the study and summary of the contents are given. These tasks are described in detail in the subsequent chapter.

Following in the introductory chapter, Chapter 2 will overview a compressive literature survey on explaining the details such as machining model development by various researchers, application of numerical formulations, effect of frictions, heat generations and temperature distribution during machining and tool wear progress will be described in this chapter.