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A Preliminary Design of a Hybrid Machine for Additive and Subtractive Manufacturing

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Abstrak.
Manufaktur aditif (AM) atau biasa disebut pencetakan 3D (3DP) dan purwarupa cepat (RP) adalah teknik pencampuran bahan dengan cara fusi, mencampur, atau memadatkan. Meskipun banyak keuntungan dari AM, namun ada kelemahan dari AM seperti kualitas permukaan mungkin tidak sebagus proses pemesinan subtraktif (SM), oleh karena itu akan lebih baik untuk memiliki proses pembentukan bentuk awal dengan AM dan kemudian menyelesaikan permukaan yang diperlukan. dengan proses SM dalam satu pengaturan. Makalah ini menyajikan desain awal mesin hybrid AM-SM untuk memproses bahan berbasis resin. Desainnya mencakup desain struktural dan sistem kontrol mesin dengan menggunakan bahan dan firmware yang banyak tersedia di pasar.

Kata kunci. *Aditif, Subtraktif, Manufaktur, Mesin Hibrida*

Abstract.
Additive manufacturing (AM) or commonly called 3D printing (3DP) and rapid prototyping (RP) is a technique of blending materials by either fusion, binding, or solidifying materials. Despite many advantages of AM, there is a drawback of AM such as the surface quality may not be as good as subtractive machining (SM) process, therefore it will be better to have the initial shape forming process with AM and then finishing the required surface with SM process within a single setup. This paper presents the preliminary design of hybrid AM-SM machine to process a resin based material. The design includes structural design and control design of the machine using the material and firmware widely available in the market.

Keywords. *Additive, Subtractive, Manufacturing, Hybrid Machine*

Introduction

The manufacturing process is a production process that results in changes in the shape or dimensions of the product. These processes are outside the transportation, handling, and storage of products, because they are not directly related to changes in the shape or dimensions of the products. Manufacturing processes can be in the form of subtractive and additive. Other categories of manufacturing process includes joining, splitting, and transformative.
Subtractive manufacturing is the process of forming parts by removing unwanted material from the work piece using cutting tools. This can be done by a manual process or by using a machine tool, either traditional machines or computer numerical control (CNC) machines driven by an NC code generated from an integrated CAD/CAM (computer aided design/computer aided manufacturing) systems. In contrary, additive manufacturing is the process of forming a part by gradually adding material layer by layer. In joining processes, two or more metal parts are combined to produce the desired shape and dimension of the product. The unification process is carried out by pressing, welding, using rivets or bolt-nut, and other assembly methods. The join can be generally permanent or non-permanent connection types. Splitting process is the opposite of the joining process, for example sawing and dismantling. In transformative process, single work piece is used to produce another work piece, by keeping the same mass. Forming, heat treatment, and cryogenic cooling are among this processes.

Based on the ASTM definition, additive manufacturing (AM) is the process of combining materials to create objects from 3D model data, usually layer by layer, as opposed to subtractive manufacturing methodologies. Other terminologies to describe additive manufacturing includes additive fabrication, additive processing, additive engineering, additive coating, and free form fabrication[1]. Other widely used terminologies are 3D printing (3DP) and rapid prototyping (RP). This definition applies broadly to all classes of materials including metals, ceramics, polymers, composites, and biological systems. Although additive manufacturing has existed as a method for processing materials for more than two decades, it has only recently begun to emerge as an important commercial manufacturing technology. CAD 3D data is converted into STL (Standard Tessellation Language) format then is sent to AM machine to produce the desired components. The benefits of AM are obtained when low production volumes, high design complexity, and frequent design changes are required, by overcoming the design constraints of traditional manufacturing methods. However, AM applications produce parts with low accuracy and long processing times compared to CNC machines. In addition, unlike conventional production processes, AM consists of additional controllable process parameters and higher active interaction between the material properties and process parameters.

One of drawback of AM is the surface quality may not be as good as subtractive process, therefore it will be better to have the initial shape forming process with AM and then finishing the required surface with CNC milling process within a single setup. In order to do that, theis research will focus on developing a framework for building a hybrid machine that can do both Additive and SubtractiveManufacturing.

Preliminary Design Methodology

Review of Current Technologies

Investigation has shown, hybrid concept systems have the potential and effective use for high functionality mold production, Near-net shape manufacturing, repair processing and coating. There are a number of companies which have launched hybrid machine incorporating Selective Laser Melting (SLM) technology and milling function as a solution for high functionality mold manufacturing [2]. Other companies focus on the rest of three potential applications. Basically, Directed Energy Deposition (DED) technology has the advantage in these applications compared with Powder Bed Fusion (PBF) method including SLM.

Among the different metal additive manufacturing technologies available, the industry has predominantly opted for PBF and DED processes [3]. Almost any weldable metal can be processed with any of these two techniques. Nevertheless, the vast majority of hybrid systems integrate Laser Metal Deposition (LMD), which is a DED technology that is faster than SLM, a PBF process, and does not need any process chamber nor supporting structures [4, 5]. For instance, in LMD typical deposition rate values of 5-30 g min-1 are obtained, whereas the SLM process presents typical values of 2-3 g min-1. In addition, this approach is adaptable to existing conventional machine tools. Hence, hybrid machines give rise to new opportunities in the manufacturing of high-added value parts, cnabling the high-efficiency production of near net shape geomctries, as well as the repair and coating of existing components [6]. Besides, the capability to switch between laser and machining operations during the manufacturing process enables finishing by machining regions that are not reachable once the part is finished. In Figure 1, the main additive and subtractive process combinations are shown. They are divided into two groups according to the additive approach in which they are based on. It is noteworthy mentioning that while PBF based processes are mainly directed to produce complex whole parts, DED processes are more focused on the generation of coatings. That is why the latter can be combined with a wider range of subtractive processes.

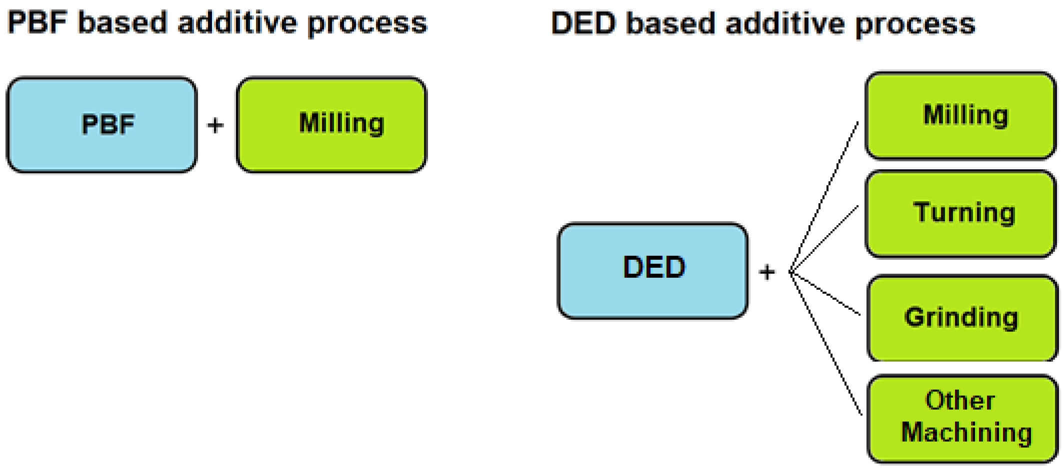

Figure 1. Different process combination in existing hybrid machines

Obviously, the hybrid system has only been employed for metal additive manufacturing and there is no company found developing hybrid system for non metalic materials such as ABS (Acrylonitrile Butadiene Styrene), PLA (Polylactic Acid) or carbon fiber. The finishing of ABS or PLA part would be needed for a certain product such as the pattern for investment casting. Therefore, this research focuses on designing the hybrid additive and substractive manufacturing system for processing ABS material, due to the fact that ABS is best suited for applications where strength, ductility, machinability and thermal stability are required. However, precausion need to be taken because ABS is more prone to warping.[7].

Preliminary Design of Mechanical Component

The hybrid AM SM machine is designed to have travel distance of X 800mm, Y 700mm, and Z 600mm as shown in Figure 2. The author uses several materials such as Aluminum 6063-T5 and aluminum 6061. The mechanical properties that are usable in the research are Yield strength, Tensile strength, Density, Shear strength, Shear modulus and Modulus of Elasticity as it is shown in Table 1. Aluminum 6063-T5 and aluminum 6061in this design are used as the base material of frame and V-slot.

Table 1. Mechanical properties of aluminum 6063-T5 [8, 9]

Properties	Aluminum 6063-T5	Aluminum 6061
Elastic Modulus	68,900 N/mm^2	68,900 N/mm^2
Poison's ratio	0.33	0.33
Shear modulus	25,800 N/mm^2	25,800 N/mm^2
Shear Strength	117 N/mm^2	207 N/mm^2
Mass Density	2,700 Kg/m^3	2,700 Kg/m^3
Tensile Strength	186 N/mm^2	310 N/mm^2
Yield Strength	145 N/mm^2	276 N/mm^2

Aluminum 6061 in this design is used in parts which support the machining process, mostly for plate and mounting such as X-plate, Gantry Plate, Z Plate, Spindle Mounting, Corner Bracket, Plate of Rod, and L cover Plate.

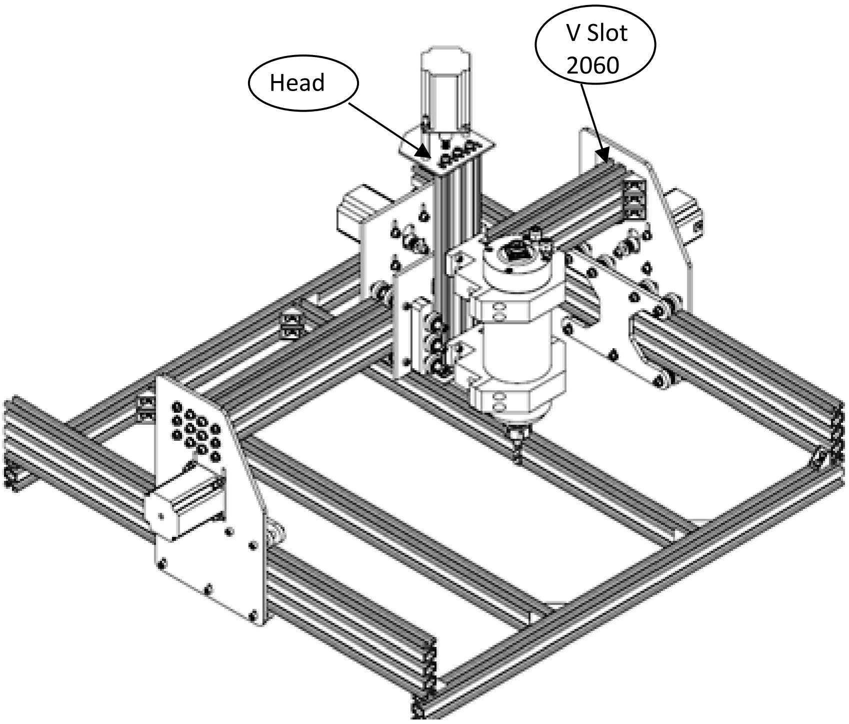

Figure 2. Design of hybrid AM SM machine

V-slot

V-slot 2040 is an ordinary V-slot in general, the 2040 number on its end indicate its dimension. 2040 mean is, the wide and the height of the V-slot which has the amount of 20mm x 40 mm. There are two kinds of V-Slot 2040 in this design, the first one is long and the second one is short. The long one has the total length of 700mm and the short one has the total length of 660mm. Look at the Figure 4. for the details. V-slot 2040 long in this design is used as the stand for the machine to the ground, and V-slot 2040 short used as the stand for the bed of machine. V-slot is this design is made from aluminum 6063-T5.

V-slot 2060 is an ordinary V-slot in general, the 2060 number on its end indicate its dimension. 2060 mean is the wide and the height of the V-slot which has the amount of 20mm x 60 mm. There are two kinds of V-Slot 2060 in this design, the first one is long and the second one is short. The long one has the total length of 700mm and the short one has the total length of 300mm. V-slot 2060 long in this design is used as the stand for the X-axis movement and V-slot 2060 short is used as the stand for the spindle mounting, so not only the Spindle could be mounted on X-axis, but also could be adjust as the desired. The V-slot 2060 short and V-slot 2060 long is made from aluminum 6063-T5.

V-slot 2080 in this design is used as the stand for the Y-axis, it is directly contacted with the V-slot wheel. The reasons why the author using V-slot 2080 instead of another V-slot is because of its height which is about 80mm, such height is needed to increase the inertia and reduce the stress bending on the V-slot 2080, also strengthen the structure because of the V-slot 2080 would stand against weight force of its upper body. The V-slot 2080 is made from aluminum 6063-T5.

Bending Stress and Deflection on V-slot 2060

In this design the V-slot 2060 is restrain the weight of the Head Sub-assembly on the machine. This component is considered the most critical part in the machine that need to be designed and analyzed. In this matter of case the stress bending would occur on long V-slot 2060. From the calculation we knew that the mass of the Head Sub-Assy is 10.8825 kg almost reach 11 Kg, and distributed into every single wheel out of 6 wheel which is restrain by two pieces of V-slot 2060 long look at the Figure 2 for the details. If we analyze the figure above, and we assume that the force is centered in the middle of the V-slot 2060 which would cause the maximum bending stress. The stress bending that happen in the V-slot 2060 is calculated using formula below

$$\sigma_b = \frac{M \times y}{I}$$

$$= \frac{9491.898Nmm \times 29.885mm}{147689.7mm4}$$

$$\sigma_b = 19.2059 \text{ MPa}$$

Since we knew that the allowable stress is equal with the yield strength divided by the safety factor, and the safety factor for V slot 2060 is taken as 4, then the Allowable stress the calculation is as follows:

Allowable stress = Yield Strength / 4

= 145/4 = 36.26 MPa.

The deflection on the V-slot 2060 could be calculated using formula below

$$\delta_{max} = \frac{F \times L^{\wedge}3}{192E \times I}$$

$$= \frac{107.91N \times (703.69mm)^{\wedge}3}{192 \times 68900N/mm2 \times 147689.7mm4}$$

`` = 0.019245765 mm

Stepper Motor

Stepper motor is an electromechanical device which converts electrical pulses into discrete mechanical movement. The author uses the stepper motor because of several reasons due to its advantages. First, motor stepper has excellent response to starting, stopping, and reversing. Second, stepper motor has a precise positioning and repeat ability of movement. Third, it is possible to achieve a very low speed synchronous rotation with a load that is directly coupled to the shaft. Stepper motor has a lot of type depends on its power and specific purposes, in this research the author uses the Nema 23 as the motor stepper for the main part to move the x, y and z axis. Motor Nema 23 is a stepper motor with the dimensions of length width and tall 104.39mm x 57.15mm x 57.15mm. The example of stepper motor drawing and dimension can be seen in Figure 3.

The stepper motor Nema 23 specification is listed as follow:

- Maximum Rpm (rotation per minute) = 900
- Continuous operating torque 35in.oz
- Overhung capacity load 15 lbs or 6.8 Kg
- Full step Increment 1.8°
- Full step per second 3,000

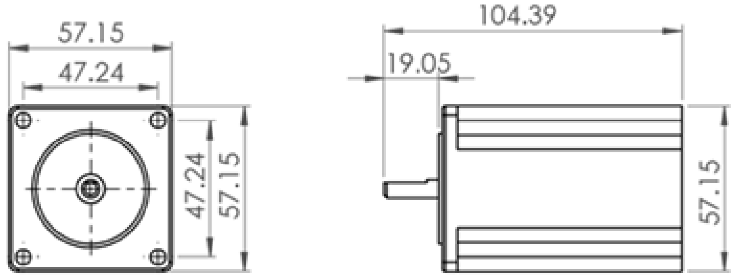

Figure 3. Stepper motor Nema23 drawing

Spindle Motor

A spindle motor is a small, high-precision, high reliability electric motor that is used to rotate the shaft or in this case the end mill cutter. This spindle motor is used to rotate the end mill cutter so the end mill cutter could cut the workpiece.

The spindle specification is listed as follow:

- Voltage is 220Volt-250Volt
- Power is 2.2 Kw
- Speed is 8000-24000 R/min
- Frequency 400 Hz

Extruder

The extruder in 3D printer ejects material in liquid or semi-liquid form and lay down the material on the bed in successive layers to form the desired geometry according to the design. There are 3D printers that use the extruder to only deposit a bonding agent serves to solidify a powder form material. The function of the 3D printer extruder is very essential in additive manufacturing processes..

Figure 4. Spindle motor [10] and 3D Print Extruder [11]

In order to enable changing extruder to mill spindle and vice versa an attachement is needed to be designed for fast change over. Another way is to design the headstock to be able to hold both milling spindle and 3d print extuder on both ends and able to rotate 180O in order for tool change over.

Control System Preliminary Design

The design of this hybrid AM-SM machine working with a 3 axis mechanism, the control system on the machine uses a microcontroller. Some important components contained in the machine control system include Computer, mainboard MKS Sbase 1.3, Motor Driver, Stepper Motor, Spindle motor, Extruder, Power Supply and others. The computer is the command center on the machine, where all the commands that will be delivered to the machine in the form of G-Code or NC file come from the computer. In general, all types of computers can be used for control systems that have been designed with Windows 10 operating system.

The critical component contained in the machine control system is MKS Sbase 1.3. This tool is the brain of all control system components. This tool functions to translate commands in the form of G-Code and then conveyed to the actuator driver and extruder driver. Actually there are several types of microcontroller available in the market, both Arduino based and other controller based. However, due to various considerations, it was decided to use the MKS Sbase V1.3 as a machine control system. MKS Sbase 1.3 can be controlled via the code written in Arduino IDE. Besides being one of the best controller, it is relatively cheaper price, and the availability in the market is quite a lot.

Calibration of the control system is needed to ensure the machine is able to carry out the printing or cutting process accurately and precisely. To maintain the machine's security system so that it moves as it functions, the machine is equipped with an emergency stop. If at any time the movement of the machine out of control can endanger the workpiece, the machine, or people around the machine, then the emergency stop button can be pressed so that the machine can stop immediately.

The type of machine control system in this study is open loop. By using MKS Sbased microcontroller, as a G-Code translator, pulses are sent to the actuator driver and extruder or spindle. The control system block diagram is shown in Figure 5.

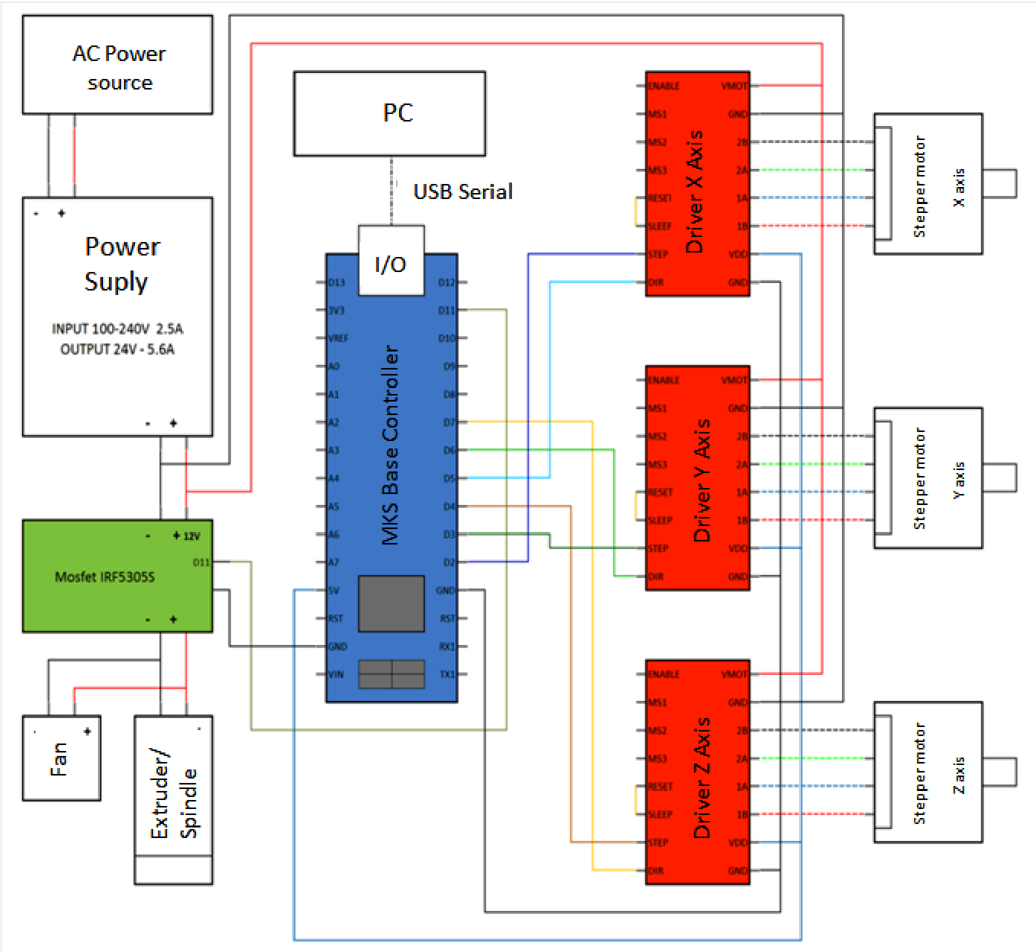

Figure 5. Control system block diagram

The design of an actuator control system on a hybrid AM-SM machine uses a stepper motor as a driver of the X, Y and Z axes by using the A4988 type stepper driver with a rating scheme as in Figure 6.

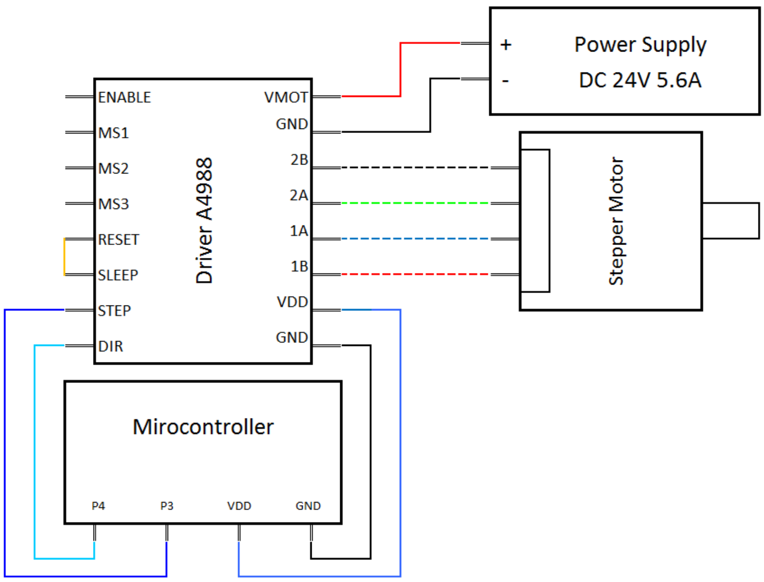

Figure 6. Actuator control system

To move the stepper motor, we must give a 5 V pulse voltage to the 4 pin stepper motor with a certain sequence pattern. One particular sequence will move one step (1.8O). Turning one full turn of the stepper motor (360O), is done by repeating 1 step 200 times from the following calculation (360O / 1.80O = 200 steps), to move one step then the 4 pins must be given a pulse with four steps as in Table 2 .

Tabel 2. Step sequence

Step	Pin1	Pin2	Pin3	Pin4
#1	LOW	LOW	HIGH	HIGH
#2	HIGH	LOW	LOW	HIGH
#3	HIGH	HIGH	LOW	LOW
#4	LOW	HIGH	HIGH	LOW

Controller Board

For the purposes of this preliminary design, the mainboard to be used is selected from the available 32 bit board using open source firmware, they are Duet Wifi, Replicape, Re-ARM, Arduino DUE, Smoothieboard, Archim, and MKS Sbase 1.3 [12]. From price and performance wise, the author select MKS Sbase 1.3.

Firmware and Control Sofftware

Among the popular 3d printer firmware and control software in the market, the author select an open source firmware and control software such as Marlin, Repetier, Reprap, and Smoothieware [13]. The firmware should also be able to control the CNC machine operation.
Marlin can support many number of controller board and is a rock solid choice for running Cartesian 3d printer. One limitation is its non-compatibility wit 32 bit controller board, which means the printer can not run at top speed with Marlin. Marlin require Arduino IDE to set the configuration.
Repetier firmware work very well with Repetier Host as the control software, and it supports 32 bit controller boards. Similar to Marlin, Repetier also need Arduino IDE to set the configuration.
Reprap was originally designed for Duet controller board, setting and updating configuration in Reprap is as simple as changing a text file. It is the only firmware to come with a complete web based interface. One limitation is that Reprap work only with a small number of boards,
Smoothieware was written for Smoothie board, updating this firmware and configuration is straightforward , just loadinng a configuration text file and firmware binary file onto a SD card. Like Reprap, Smoothieware only works with limited number of boards.
Since the selected board is MKS Sbase 1.3 board, the most suitable and convenience firmware and control software is Repetier firmware and Repetier Host.

Result and Discusion

From the previous calculation, the working bending stress on the long V Slot 2060 is 19.21Mpa. Since we knew that the allowable stress is equal with the yield strength divided by the safety factor, and the safety factor for aluminum 6063-T5 is considered 4, then the calculated Allowable stress is 36.26 Mpa.
From the result above we could summarize that the working stress of 19.21Mpa is far lower than the allowable bending stress, which is 36.26MPa. it is mean that the working bending stress did not exceed the allowable stress and we could state that the design is safe.
Similarly with the maximum deflection on this V slot, the deflection limit for high precision component is 0.00001 to 0.0005 inch/inch or the same as 0.00001 to 0.0005mm/mm [14]. Since the length is 703.69 mm, then the deflection limit for the v-slot 2060 is 0.0005×703.69mm = 0.3519mm or 351.9µm. From the result above we could summarize that the maximum deflection of the V slot 2060 is 19.25 µm < 351.9µm. and we could conclude that this design is safe.

The machine control system is built to effectively control X, Y, and Z stepper motors as well as spindle motor and printing extruder. The controller board is MKS Sbase 1.3 and the firmware used to control the motion is Repetier. The control software to operate the machine is also Repetier Host.

Conclusion

This preliminary design of hybrid AM-SM machine is mainly focused on analysing the machine structure and control system. The machine having dimension of 800mm x 700 mm x 600mm is able to restrain its normal weight according to calculation. The firmware, software, controller, and other control system component use the widely available component in the market for easness of finding the appropriate components.

After the machine was completely built, a series of testing need to be carried out to ensure everything working properly such as system control and actuator control function tests. The print and cutting quality test are also needed to be done before the machine can operate properly.

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