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Design and Fabrication of Compact CNC Hot Wire Foam Cutting Machine

Sanjay S N[1], Sidhvin D M[2], Sachin Hegde[3], K P M Unni Krishnan[4]

Under the guidance of - **Dr. S V Satish**
Department of Mechanical Engineering, PESIT Bangalore South Campus, Bangalore 560100

Abstract: ***Hot wire foam cutter is a computer controlled machine used to cut complex 3D geometries for commercial applications where a light weight material can be easily machined in a short period of time. Direct cutting of foam has the advantage of greater flexibility and reduced lead time over molding. This paper describes the design and fabrication process of a 4 axis hotwire foam cutting machine. It is a 4 Axis machine with two sets of mutually perpendicular axes separated by a certain distance. The current carrying Ni-Chrome wire is held taut between two machine heads which move linearly along the axes enabling it to cut tapered and prismatic geometries. Variation of cutting speed and temperature determines the thickness and consistency of kerf. A non-uniform feed rate can lead to kerf of varying thickness. The movement of the stepper motor is controlled by sending the G-codes to the interface board through anopen source software. It has a wide range of applications like RC model aircrafts wing and fuselage construction, Architecture scale models and props, Signage, Packaging etc.***

Keywords: Hot wire, breakout board, microstepping, Nichrome wire, cutting speed, kerf width

1. Introduction

(1)Large-sized freeform objects made from soft materials have numerous uses including; conceptual design of commercial products, automotive design, aerodynamic and hydrodynamic testing, advertising, film making, medical supports, sporting equipment, packaging and the entertainment industry. Development of foam cutting machines for rapid prototyping and manufacturing purposes began shortly after the first additive manufacturing machines became commercialised in the late 1980s. Increased computer power, the development and adoption of CAD/CAM software and rising demand for customisation has caused the rapid prototyping industry to grow swiftly in recent decades. While conventional rapid prototyping technologies are continuing to improve in speed and accuracy the ability to produce large (> $0.5m^3$) prototypes, moulds or parts it is still expensive, time consuming and often impossible. Foam cutting rapid prototyping and manufacturing machines are ideally suited to fulfill this niche because of their high speed, large working volumes and inexpensive working materials. Few foam cutting rapid prototyping machines have been commercialised to-date leaving significant opportunities for research and development in this area.

(2)Thermal plastic foam cutting is the material removal process most commonly used in foam cutting rapid prototyping to shape or sculpt the plastic foam into desired shapes and sizes. The process is achieved by introducing a heat source (generally a wire or ribbon) which alters the physical properties of the plastic foam and allows low cutting forces to be achieved. In thermal plastic foam cutting the heat source is generated via Joule (electrical) heating.

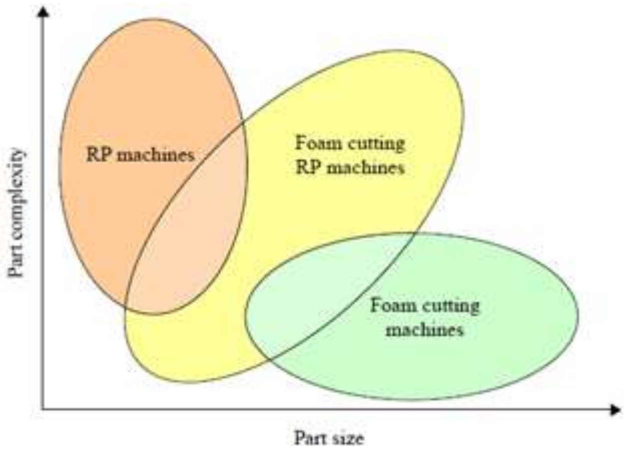

Figure 1: (3)Comparison between conventional RP machines, foam cutting machines and foam cutting RP machines in terms of part complexity and part size

2. Methodology

A current carrying heated wire is directed through a foam block. The melting point of Polystyrene foam is around 200°C, but it attains a flowing state at 100°C. The heated wire has a temperature of 204°C. Hence the wire locally vaporises the foam at the cutting location. This partially melts the foam surface and leaves an open gap at the cut location. This gap is called kerf. **Kerf width** is a function of cutting temperature and cutting speed. It increases with increase in temperature and reduces with increased cutting speeds.

3. Overview of Parts Used

a) **Frame:** A 19.04mm thick plywood sheet was used to construct all the major parts of the machine. It was easily available in a standard size of 1.82m x 1.21m
   - Base: A 1.21m x 1.21m, 19.04mm thick plywood sheet was used as a base on which all the parts were mounted. It also supports the foam work piece during the cutting operation.

- Towers: A 500mm vertical tower on which the vertical moving head moves for linear vertical motion of the wire is constructed. This entire assembly moves horizontally along the base for linear horizontal motion of the wire.
- Support frame: 4 support frames are constructed on which the upper guide rod is mounted. This prevents any wobbling or leaning in of the vertical towers due to their weight.

b) **Movement:** The horizontal movement is supported by 3 12mm hardened stainless steel shafts. 2 shafts are mounted on the base and the other is mounted on support frame at all 4 corners of the base. 12mm linear sliding blocks slide over these shafts and are rigidly mounted on the vertical towers. A long nut welded to a flat plate is mounted rigidly on the bottom face of the vertical tower. An M10 ACME threaded rod is used to move the towers accordingly. These threaded rods are coupled to the stepper motors with custom manufactured couplers held rigid to the motor shaft using perpendicular grub screws.

Figure 2: 12mm linear sliding block

c) Electronics: One of the key features of this project is the simple electronics employed. The connections are simple and the setting-up time is relatively low. There is no coding or flashing of code required as most of it is plug-and-play type of connections

- **Motors:** NEMA 23 stepper motors with a torque of 15Kg-cm is used. This high-torque motor is used despite the low cutting forces due to the weight of the large moving parts.

Figure 3: (4) NEMA 23 motor

- **Drivers:** A 2 phase stepping motor driver from Toshiba, TB6560 is used to drive the NEMA 23. This driver gives a range of operating currents ranging from 1A to 3A. It also has dip switches which provides flexibility for choosing the micro-steps from a range of 1/2 to 1/16.

Figure 4: (5)TB6560 driver board

- **Breakout board:** A breakout board is an electronic circuit that breaks out bundled connections into easily accessible connections. A 5 axis breakout board with an opto-coupler to protect the controlling computer from high external voltages was selected. It has options for E-stop switches and spindle control. It interfaces with the controlling computer via a 25-pin parallel port. It shares a common ground with the PC via a standard 5V USB cable.

Figure 5: 5 axis breakout board

- **Power supply:** The motors operate at 24V DC. The entire stepper motor set up is powered by a 24V DC Switch Mode Power Supply.

4. Theoretical Maximum Cutting Speed

Lead screw pitch: 2 mm/rev
Maximum speed of stepper motor: 300 rpm
Hence, the maximum linear motion of an axis is **600mm/min**. This is the maximum cutting speed of the machine. But due to the low tensile strength of the cutting wire, the cutting speed is reduced to achieve accurate cuts.

5. Open Source Software (Linux CNC)

To reduce costs, an open source CNC control software called Linux CNC (6) (called EMC2 earlier) was used. It is a Linux based operating system created solely for the control of CNC machines. It uses the parallel port of the computer to interface with the CNC machines. It has the flexibility to use multiple parallel ports if the given number of pins are insufficient.

The setup process begins with the Stepconf application which allows the user to setup the machine in terms of number of axes, limit switches, motor driver settings, microstepping, maximum speed and acceleration of the motors and the working area of the machine. The settings are saved as a .ini file which can be edited if necessary.

The machine control application is then launched which can remotely turn ON/OFF the machine and Enable/Disable Emergency stop. All the axes are homed and the required G-code is then opened. The G-code is then checked for errors and the program is run. The GUI of Linux CNC, called Axis (7), plots a real-time simulation of the tool head. The G-code is then saved for future reference. In this project, we have the flexibility to setup the machine as a 2-axis or a 4-axis machine.

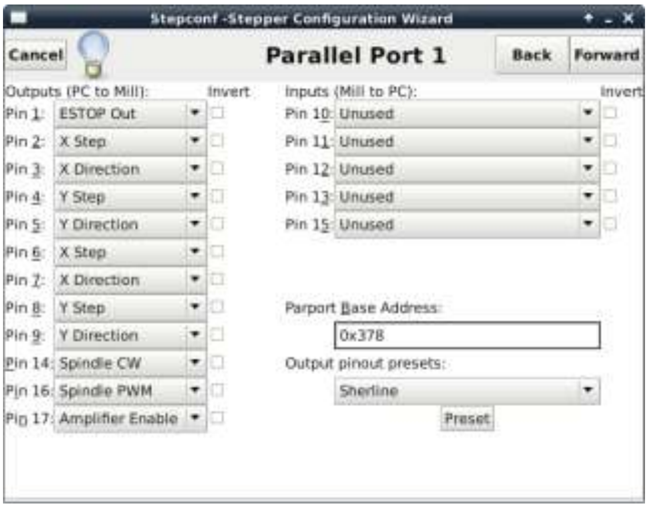

Figure 6: Stepconf setup page for 2 axis

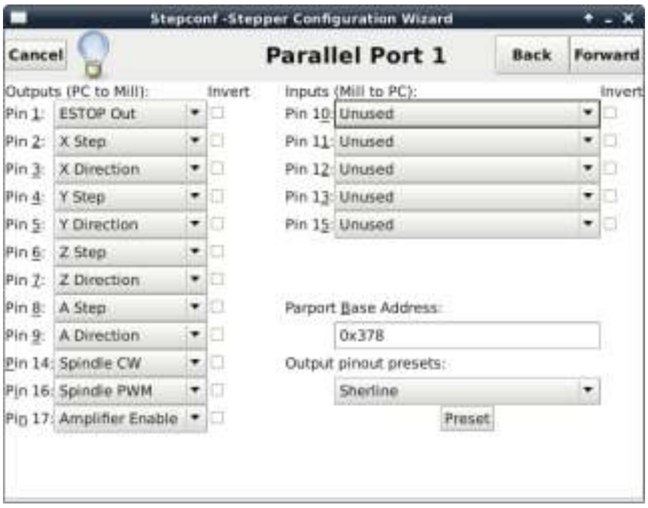

Figure 7: Stepconf setup page for 4 axis

6. NiChrome wire data

Nichrome (NiCr, nickel-chrome, chrome-nickel, etc.) are alloys of nickel, chromium, and often iron (and possibly other elements or substances). The most common usage is as resistance wire. In this project, we use Nichrome wire for the Joule (Electrical) heating.

The following table (8) gives the current requirement (A) to heat different gauges of wire of a standard length to different temperatures.

AWG	Diameter (mm)	204° C	537° C	1093° C
8	3.251	22.4	52	128
10	2.591	16.2	37.5	92
12	2.057	11.6	26.5	65
22	0.643	2.9	5.6	12.5
32	0.2032	0.68	1.36	2.76

Figure 8: Approximate current (A) to heat a straight oxidized wire to a given temperature

From these tables, the most suitable wire was found to be 22 gauge wire which attained a temperature of 204° C when a current of 3A was passed through it. This temperature was found to be sufficient for the cutting process.

7. Design Calculations

Stepper Motor Selection calculations

- Mass of components including spindle(approx): 4Kg
- Fm = 4x9.81 = 39.24N
- Frictional Force
- Ft = μ*Fm = 0.2x39.24 =7.848N
- Force required for pushing the wire into work piece for machining
  Fc = 20N(approx)
- Total Force: FT = Fm+Ft+Fc
  = 39.24+7.848+20
  = 67.088N

Formulae to calculate the Screw rod(M10) Force

- T= F*(tan(α+φ))
- tan α = P/(π*d) = 1.5/(π*9.25) = 0.0502 where α = 2.95 degree
- Dm = Do-(P/2) = 10-(1.5/2) = 9.25mm
- Tanφ = μ/cosβ = 0.2/cos15 = 0.2/0.966 = 0.207 where φ =11.69 degree
- T = torque in N-mm

Therefore :

- T = F*tan(α+φ)
- T = 67.088*tan(2.95+11.69)
- T = 17.525N-mm

Considering Factor of Safety of 3
Treq = 52.575N-mm
Standard motor Torque available in market **= 294.3N-mm**

8. Construction Procedure

The construction of any CNC machine demands high level of accuracy in the fabrication of its moving parts. To achieve this level of accuracy, all the components were designed on a CAD software. These designs were printed to scale. These prints contained the edges and holes required in that specific component. They were then stuck to the surface of the plywood sheet and the edges were cut and the holes were drilled according to the prints.

Figure 9: Final constructed machine

9. Tests and Results

A simple G-code was written to cut out a small circle of 20mm diameter. It was programmed to linearly travel 50mm into the foam diagonally and then cut a circle of 20mm diameter.

The entire cutting operation took 51s. The kerf width was found to be 1.5mm. It was concluded that a faster cutting speed results in lesser kerf width but also increases the stresses in the cutting wire.

It is a trade-off among these parameters :- Cutting speed, Cutting Temperature, Kerf width.

Increasing the cutting speed, reduces the kerf width but also increases the stresses on the cutting wire. This increases the chance of wire failure. Decreasing the cutting speed, increases the kerf width and compromises on the surface finish due to excessive warping.

Hence several trials were conducted and the optimum cutting speed was achieved.

Figure 10: Test cut

Some of the other test results for different shapes are as shown below:

Rectangular model

	Trail 1	Trail 2	Trail 3	Trail 4
Kerf Width	1.39mm	1.06mm	0.86mm	0.58mm
Speed	150mm/min	286mm/min	339mm/min	469mm/min
Error	0.15mm	0.139mm	0.121mm	0.11mm

$$\%Error = 0.64\%$$

Hexagonal model:

	Trail 1	Trail 2	Trail 3	Trail 4
Kerf Width	1.2mm	1.06mm	0.9mm	0.79mm
Speed	140mm/min	286mm/min	339mm/min	469mm/min
Error	0.17mm	0.119mm	0.15mm	0.11mm

$$\%Error = 0.102\%$$

Wing airfoil section:

	Trail 1	Trail 2	Trail 3	Trail 4
Kerf Width	1.4mm	1.3mm	1.1mm	0.98mm
Speed	140mm/min	286mm/min	339mm/min	469mm/min
Error	0.22mm	0.19mm	0.15mm	0.1mm

$$\%Error = 0.5\%$$

Other miscellaneous test specimen -
Alphabets:
Gear profile:

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