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A NEW ADAPTABLE RAPID PROTOTYPING & MANUFACTURING APPROACH FOR PRODUCING A VARIETY OF FOAM-BASED PRODUCT SOLUTIONS

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Abstract

Rapidly changing consumer and engineering product market trends have dictated the need for manufacturers to produce goods that can either be readily configured to the shifting market and/or be created by an adaptive manufacturing process. Only through implementing this strategy can the associated companies remain competitive in the global marketplace and grow their market sector. This paper presents recent research findings which are pivotal in enabling a manufacturing facility that satisfies the latter need identified above: The work will ultimately culminate with the creation of an innovative and adaptable Rapid Prototyping and Manufacturing (RP&M) facility. Specifically, the objectives of the reported experimental work were to establish suitable types of wire for the hot-wire cutter and determine their related surface finish and cut accuracy effects; when cutting expanded polystyrene (EPS) foam sheet under a range of cutting conditions.

1 Introduction

Flexible and rigid expanded foam materials have a variety of uses that are rapidly proliferating, inline with the demand for consumer goods and heightening lifestyles. Casual observation reveals a number of common applications, which span a diverse range of product sectors that include automotive, domestic goods, furniture, architectural detailing, aviation and marine [Klempner & Frisch 91, Negussey 98]. Most of these applications involve the use of components that posses free form surfaces, generally for aesthetic or ergonomic reasons. Within the above-identified sectors and others that are experiencing rapid growth and diversification, such a sports equipment and biomedical applications [Dovorany 01], there is a demand for the various foam-based constructions to be heavily customised and/or posses unique design solutions. Currently, creating unique or customised shapes requires skilled sculptors/technicians as only basic profiling machines are normally accessible which are limited to cutting in 2½D. In some cases, automated multi-axis hot-wire machines are available that extend the forming capability to produce ruled surfaces and 3D shapes. However this technology does not support the production of 3D free form, concave or intricate surface detail, which is commonly required at human/product interfaces and in many modern products/artefacts. In light of this shortfall a need was identified for an automated manufacturing capability that can rapidly and accurately produce unique complex foam components in desired forms. Consequently a research programme was proposed aimed at developing a novel hot-wire foam cutting machine which would surpass these limitations.

An initial literature survey indicated that little work had been published on the performance and optimisation of the critical performance parameters for the proposed foam cutting application. Subsequent reasoning led to the decision that the hot-wire cutting performance was dependant upon three main factors: wire temperature, cutting feed-rate and wire composition. Therefore, a series of controlled cutting tests were proposed to quantify the optimised conditions. Specifically, the objectives of the reported experimental work were to establish suitable types of wire for the hot-wire cutter and determine their related surface finish and cut accuracy effects; when cutting expanded polystyrene (EPS) foam sheet under a range of cutting conditions.

This fundamental experimental work has now been completed and the findings are reported below.

2 Experimental procedure

At the outset of the work, a simple fixture was developed to cut foam materials using the taut hot-wire technique. The device was designed to slice expanded foam samples using a sweeping one-dimensional (1-D) linear movement, essentially by feeding the hot-wire horizontally towards and through a foam test sample. To simplify the development task and to minimize cost the fixture was devised to attach to the spindle housing of a standard industrial milling machine (see figure 1). In this configuration the linear movement and feed rates were all readily available machine functions and could be easily altered to meet the demands of the proposed tests.

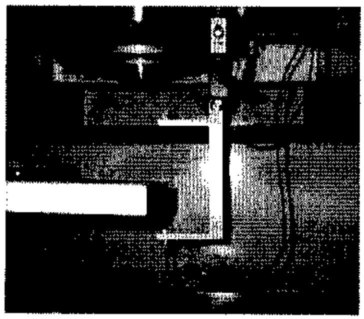

Figure 1. Test setup showing hot-wire fixture and milling machine working envelope

The configuration introduced above was used in a series of specification and cutting optimization tests. The test objectives were as follows:

i. To determine qualitatively if there was a wire type that was more suited to the hot-wire cutter than any other,

ii. To establish suitable feed rate and wire temperature combinations which could be used to slice foam under normal cutting operations,
iii. To isolate optimal cutting conditions (feed rate and wire temperature), from the above ranges, which provide minimal dimensional error and superior surface finish at the cut surface.

The adopted test material was polystyrene with standard measurements of 300mm wide, 300mm long and 50mm thick. Polystyrene was chosen as it is the most widely used expanded foam material that has a multitude of practical engineering uses, can be readily cut with a hot-wire and is relatively cheap. The above sheet sizes were specified so that the units could be easily handled and transferred between the various pieces of equipment used in the tests.

The sample wires used as the hot-wire cutting tool were Nickel Chromium Alloy (Nichrome), Inconel and Nickel-Chromium-Iron (NiCr type C or NiCr-C) spring wire. Nichrome wire was specified, as it is the most commonly used wire for cutting polystyrene materials [British Driver-Harris Co. 87]. Whereas the reason for selecting Inconel and the NiCr-C spring wire was due to their ability to maintain their shape after being subjected to the anticipated operating cutting temperatures [Bauccio et. al. 93, Shanker et. al. 01, Gisser et. al. 94], an essential feature for the proposed application.

In the tests, the polystyrene sheet was cut using the different types of wire at different temperatures and feed-rates. The feed-rate ranged from 100mm/min to 500mm/min. The polystyrene sheet was cut successively under different cutting conditions (temperatures and feed-rates) at parallel offsets of 10mm per cut. Between each successive cut the material sample was demounted from the milling machine bed and placed on the bed of a Coordinate Measuring Machine (CMM). The CMM was programmed to determine measures for surface form (used to assess surface roughness) and surface location (surface accuracy). A test to determine the optimum number of CMM probe touch points was conducted prior to the commencement of the cutting tests. Touch points sequences comprising 10 to 200 touches were investigated with longer measurement times being required for higher number of touches. The results indicated that surface form measurements derived from 20 through to 200-touch sequences were in close agreement. Therefore, a 20-touch sequence was adopted in the cutting tests.

The apparatus required to perform the tests was as follows:-
i. Hot-wire cutter fixture. Designed as an inverted 'F'-shape so that the vertical stem of the cutter frame could be connected to a Computer Numerically Controlled (CNC) milling machine spindle housing. Figure 2 shows the inverted 'F'-shape hot-wire fixture with open-looped wire mounting holes. The frame was designed in this way to ensure that the hot-wire would slip away from the holder if the cutting feed-rate was too fast. Teflon bushes were used to electrically isolate the hot-wire from the metal 'F' frame.
ii. Foam mounting fixture. So that the foam sample could be relocated precisely in the milling machine and CMM successively a special fixture was developed onto which the foam sample was permanently mounted. Full kinematic support was provided for the mounting fixture on the milling machine bed while the CMM simply redatumed the mounting fixture each time, upon initiation of the automatic part measuring program.
iii. CNC milling machine. A standard industrial milling machine was used to ensure that the feed-rate and linear movement of the hot-wire fixture could be accurately applied and manipulated as desired.
iv. Power source. The wire temperature was regulated by means of the applied voltage level.

v. Coordinate Measuring Machine. Measures for surface form and surface roughness were established through the use of a computer controlled CMM.
vi. Temperature sensor. A thermocouple based temperature sensor was used to record the hot-wire temperatures.

Figure 2. Inverted 'F'-shape hot-wire cutter fixture

Figure 1 shows the integrated setup of the cutting fixture connected to a CNC milling machine. As mentioned earlier, the use of a CNC mill was deemed practical to obtain a variety of feed-rates when cutting the polystyrene.

The CNC machine was set to remove a 10mm strip from the polystyrene for each successive cut. The wire radius was 0.5mm in each case. For operating temperatures ranging from 100°C up to 300°C the resultant cut depth and surface form were determined on the CMM.

To help with the validation of the above results repeatability tests were also conducted. The underlying objectives of this series of tests was to determine measures for the natural distributions of the accuracy and form results; for repeated cuts performed under 'identical' conditions. In turn these measures would provide a better understand of the cutting process capability.

The repeatability test procedure was as indicated above but the cutting feed-rate was fixed at 250mm/min and the adopted temperatures were 200°C then 250°C. These values were chosen based on the results obtained from previous tests. The taut wire was designed with a screw tensioner to ensure that it was tight and straight. The number of repeat cuts made in this test was 15 with an incremental offset of 10mm per cut, as before. After each cut the sample was demounted from the CNC machine tool and then transferred to the CMM for measuring. A selection of the results is shown below, alongside the other experimental findings.

3 Results

Figure three shows an illustrative example of the cutting accuracy results for the three types of wire used in this test. The cutting temperature was 200°C and the feed-rate ranged from 100mm/min to 500mm/min. In this case, the results show that all wires were able to perform the cutting process at feed-rates of 100, 200, 300 and 400mm/min. However, only the Inconel and NiCr-C wires were able to cut at a speed of up to 500mm/min. The other wire slipped away from the apparatus as the speed increased above 400mm/min, indicating an inability to cut effectively at the higher feed-rates. For this particular run the NiCr-C results are seen to vary quite dramatically at the higher feed-rates, though a definite trend is apparent overall. The cutting accuracy values represent the linear distance (in mm) the cut surface is away from the desired surface; specified in the CNC mill controller. In all of the cases the accuracy value is seen to be positive indicating an 'over-cut' condition. Regions of the data that hug the target value of zero millimetres indicate favourable operating conditions: the cut surface is closest to the desired size.

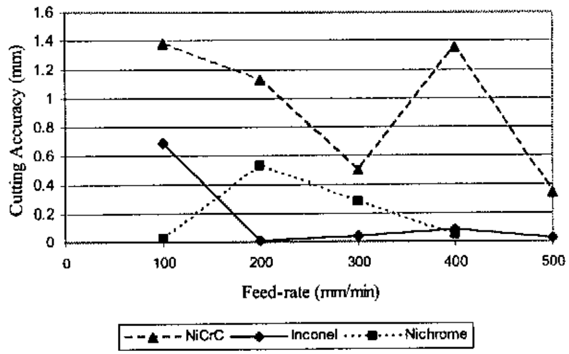

Figure 3. Cutting accuracy versus feed rate at 200°C

The surface form results in figure 4 indicate that an optimum feed rate does exist for the three types of wire when operated at 200°C. These are only a representative sample taken from the complete test data set, spanning a temperature range from 100 to 300°C.

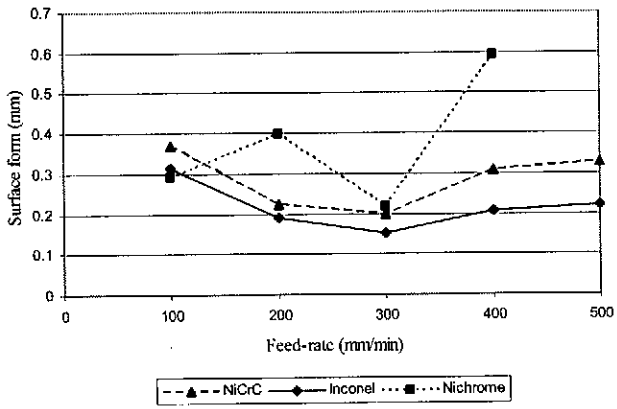

Figure 4. Surface form versus feed-rate at 200°C

The minimum turning points in the figure locate the optimum feed rates for the 200°C wire temperature, used in the associated test. To obtain the minimum surface form and therefore produce the best surface finish (at a recorded wire temperature of 200°C) the follow feed rate settings should evidently be applied for the three respective wires: NiCr-C 300mm/min, Inconel 300mm/min and Nichrome 300 mm/min. At the higher feed rates the surface form (surface finish) notably deteriorates, made apparent by the increase in the surface form values. The Nichrome results are incomplete and do not cover the higher feed rate settings due to snagging and tearing of the polystyrene, during the conducted tests. This was common for Nichrome in several of the tests, more so than the other two test wires.

Close visual inspection of the polystyrene surface also revealed the nature of the cut faces. The deep melting that occurred predominantly at lower feed rates caused the surfaces to be rough and pocketed (figure 5) while the more favourable settings produced a much smoother surface finish (figure 6). This observation largely supports the graphical results of figure 4.

Figure 5. Rough surface of cut EPS with some deep melting due to a low feed rate

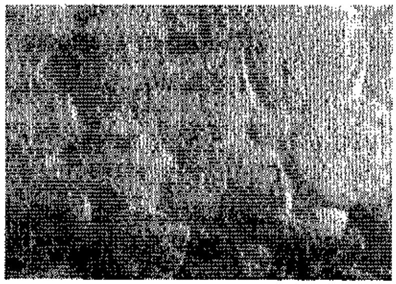

Figure 6. Smooth 'glazed' surface sample of EPS cut with hotwire

The repeatability results for the surface accuracy produced by the NiCr-C wire operating at 200°C and being fed at 250mm/min are shown in figure 7. The cutting accuracy values relate to the discrepancy between the actual measured cut width and the intended cut width of 10mm, as specified in the Experimental procedure section of this paper. Though not wholly representative, for a sample size of 15, the mean value is 0.159mm, the standard deviation is 0.063 and the range is 0.196mm for the sample.

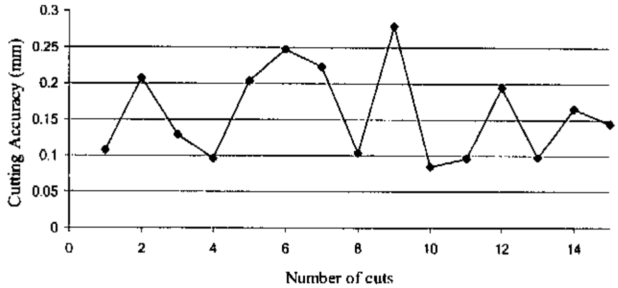

Figure 7. NiCr-C melted zone repeatability results (Temp. 200°C, feed-rate 250mm/min)

Similarly the repeatability results for the cut surface form, produced by the same wire and cutting conditions, are shown in figure 8. Again, for reference, the mean (0.264mm), standard deviation (0.038) and rage (0.120mm) values are included.

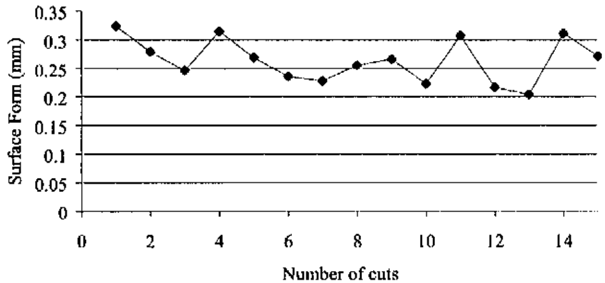

Figure 8. NiCr-C form repeatability results (Temp. 200°C, feed-rate 250mm/min)

4 Discussions

At the outset, the polystyrene surface roughness assessment exercise presented the authors with a significant problem. It was originally anticipated that the surface topology would be characterized with a standard roughness average measure such as Ra [ISO4287 84]. The widely available equipment for determining such a measure were known to be inappropriate due to their nature of operation. The most readily available recorded the vertical undulation of a sharp, needle like, stylus while drawing it over the surface to be assessed. Clearly the stylus would plough into the soft surface and produce erroneous results. A suitable alternative method for measuring surface roughness was by means of an optical technique. An initial close visual examination of the cut surface revealed areas of predominantly flat land interspersed by deep, steep-sided cavities (see figure 5). The slopes appear to be spherical in shape, as expected. It was soon established that the available optical facility did not possess the required depth of field and therefore was not be able to operate on the steep surface contours of the typical cut surfaces. Considerable time was spent trying to identify an alternative, suitable means for measuring the surface but none were found. Therefore, the authors resorted to using a Coordinate Measuring Machine (CMM) to measure the geometrical surface form of the cut polystyrene. This value was adopted as an equivalent to the desired surface roughness estimation, however it is accepted that inaccuracies are known to be present.

From the graphically recorded data a number of important fundamental findings were made. For example, a general trend is evident in the cutting accuracy results typified by those shown in figure 3. As the feed rate increases, up to a maximum of 500mm/min, the cutting accuracy tends to zero. This implies that the cutting system performance generally improves with an increase in feed rate. For a rate of 300mm/min, all of the three types of wire evidently produce a cutting accuracy of 0.5mm or better. Though all of the wires do produce improved accuracy results for feed rates in excess of 300mm/min. However, the third wire type (Nichrome) failed to operate successfully at the 500mm/min. It is believed that the reduced accuracies at lower feed rates are linked to the fact that the radiated heat from the wire has more time to melt and 'collapse' the expanded foam and therefore causes the cut surface to retreat from the desired, as cut, position. As the feed rate increases less heat is dissipated on the polystyrene surface and the cut face naturally recedes less from the traversing hot-wire. The surface form results do not necessarily concur with these assumptions.

Inspection of the surface form results of figure 4 reveals that the Nichrome wire did not perform at feed rates above 400mm/min. These values were recorded at the same time as the accuracy results and therefore suffered the same loss when the wire tore into the material, as described in the earlier paragraph. Optimal surface form values are evident by the minimum points in each of the representative curves; all coincidentally at 300mm/min. The initial high form values at low feed rate is due to excessive melting of the polystyrene by the slowly advancing hot-wire, as detailed above. Preferential melting may have occurred at 'weak' points in the foam surface. This is consistent with the magnitude of the recorded values. At the elevated feed rates the form values are somewhat higher than those achieved at the optimum feed-rate settings. This was due to one of two effects. The first was the initiation of surface tearing as the wire advanced too rapidly through the material not allowing the wire to fully melt the polystyrene ahead of its progression. This effect is most pronounced with the Inconel wire. The second effect manifested itself as striations (beach marks) on the cut surface. Though the 'microscopic' finish was essentially smooth the regular undulations contributed significantly to the surface form measures on a 'macroscopic' scale.

At this early stage in the development and testing programme a small surface form measure is desirable over the need for an accurate cut. This is because a good cutting accuracy value (low) can be artificially assumed when derived from a poor surface form value (high). However the converse situation does not stand. Therefore a cutting system that provides good surface form values is primarily desirable. From the presented results, Inconel possesses the lowest surface form value in figure 4, approximately 0.15mm. However, the slope of the Inconel curve and also the Nichrome and NiCr-C curves, typified in figure 4, indicate a sensitivity to feed rate variation. When factoring in the cutting accuracy of figure 3 the Inconel appears to be the best contender as it presents low form and accuracy values for a given feed rate, at nominally 300mm/min. The Nichrome and NiCr-C are seen to have some potential at a feed rate of 300mm/min.

It is recognized that the wire temperature could be increase significantly to support higher feed rates and therefore increase cutting productivity. However due to the need for the wire to retain its undeformed shape after being mechanically stressed at elevated temperatures, an upper temperature limit was prescribed. This took into account the wire geometry; the anticipated induced mechanical stress levels and the temperature modified yield behaviour of the wire material. Inconel and NiCr-C spring wire were nominated for the tests because of their alignment with these and other essential mechanical, thermal and electrical properties.

It was accepted that sheet-to-sheet variations in the polystyrene density could influence the attained results in a subtle way but this factor was disregarded during the tests. In support of this decision it was acknowledged that polystyrene would naturally possess a range of density values throughout a given sheet and so the cutting system settings must accommodate this.

5 Conclusions

During some of the cutting trials the wire was observed to tear the polystyrene rather than cut it by way of the radiated heat, ahead of the advancing wire. For the projected application this manner of operation was deemed unacceptable. The tearing situation essentially occurred when the feed rate was too high or the wire temperature was too low. Practical limits of operation were therefore established and feasible cutting parameter combinations identified.

The deep melting that occurred predominantly at lower feed rates and high wire temperatures caused the surfaces to be rough and pocketed (figure 5) while the more favourable settings produced a much smoother surface finish (figure 6). In some cases the higher feed rates also produced a smooth surface but striations (beach marks) resulted which gave the measured surface poor form values.

To obtain the minimum surface form and therefore produce the best surface finish (at a recorded wire temperature of 200°C) the following feed rate settings should evidently be applied for the three respective wires: NiCr-C 300mm/min, Inconel 300mm/min and Nichrome 300 mm/min.

For a rate of 300mm/min at a temperature of 200°C, all three of the wire types perform well and evidently produce a favourable cutting accuracy of 0.5mm or better. It is recognised that several factors contributed to this value and that they could be reduced to produce a system with a heightened accuracy capability. An aim of reducing the current data ranges in the presented repeatability results (cutting accuracy 0.196mm, surface form 0.120mm) is therefore essential. Effort is currently being expended on these and other optimisation endeavours.

The above reported work has contributed to an increased understanding of the factors affecting the performance of hot-wire foam cutters. The results will contribute towards completing the ongoing research and development task aimed at producing a prototyping machine that cuts foam materials using a novel hot-wire technique. The proposed system will be capable of producing freeform surfaces and concave features.

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