Analyzing the Cutting Process of a Heated Flexible Blade in Extruded Polystyrene Foam

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Reviewed, accepted August 30, 2004

Abstract

For the "Free Form Thick Layered Object Manufacturing" technology that is being developed at the Delft University, it is vital that Extruded Polystyrene Foam (XPS) can be cut accurately with a heated blade. The shape of the blade is actively controlled during the cutting process, which results in double curved cutting surfaces. In order to make this cutting process controllable it must be known how the cutting behavior is under varying conditions, like cutting speed, cutting angle and heating power. The authors executed a range of experiments, analyzed the results and describe a practical model for the cutting process of XPS with a heated blade.

Introduction

The FF-TLOM technology is being developed for the use in an early stage of the design process for large objects [3]. It combines the advantages of layer oriented prototyping technologies, like a high form freedom and ease of process planning, with the advantages of decremental technologies like low material cost and high possible production speed. The specific properties of the process make it especially applicable in the domain of large freeform shapes [2], [4]. The models produced by the system can be used as concept models during the early design stage, however the possibility of using the model as a basis for a high quality presentation model, for example by covering it with modeling clay, can be considered.

Figure 1: Free Form model out of thick layers.

The FF-TLOM technology is based on the use of layers of extruded polystyrene foam. The layers are cut in a freeform shape and than stacked. This stacking produces a 3 dimensional physical model (figure 1).

The technology can be divided in two research fields. The first field is about the decomposition of a freeform CAD model into producible layers [5]. The second field covers the production process, necessary to create the layers. The cutting tool is a part of the hardware needed for the production of layers. It exists of a flexible knife (blade) that can be heated, four actuators that can give the blade a curved shape, and a frame that connects the earlier mentioned parts. The process of cutting XPS with the mentioned flexible blade under varying conditions is being investigated this paper.

Earlier work on the topic

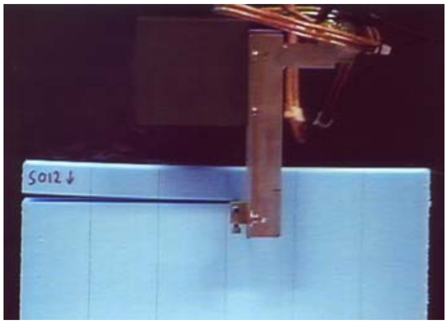
Figure 2: Cutting experiments

Not much research is known to the authors, on hot blade cutting of polystyrene foam. Viswanathan et. al. studied the process of hot wire cutting with constant speed and power [7], More recently Ahn et. al studied the optimization of the hot wire cutting process [1]. During early explorations and brainstorm sessions we generated a list of ten parameters that are influential in the cutting process namely 1) the used foam material, 2) the blade temperature, 3) dissipated thermal energy, 4) blade cross-section, 5) cutting speed, 6) cutting force, 7) blade material, 8) blade temperature distribution, 9) blade radiation pattern, and 10) maneuverability of the blade.
Reasoning about these parameters and their influence we decided that parameter 1 would be kept constant and parameters 2, 3, 5, 6 and 8 would be experimentally explored [6]. The remaining parameters would be considered in a later stage when an optimal tool design is needed. An experimental set-up was created consisting of a straight blade that can be heated using a controllable amount of electric energy. We first measured the thermal behavior of a blade when energy was supplied and made response charts concerning temperature changes, resistance changes and temperature distribution over the blade. Actual cutting experiments were executed in order to determine optimal cutting conditions for a specific type of extruded polystyrene foam (figure 2). The outcome of the experiments is a set of parameter combinations, each with an output value representing whether the resulting surface is bad, moderate or good. By combining the results in one graph we found a window within which the cutting process produces good surface results (figure 3). We see that the amount of thermal energy that is being dissipated by the blade must be roughly between 0.03 and 0.07 Joule per square millimeter foam surface. This means that by a given output power the cutting speed may vary between V_{min} and (7/3) * V_{min} . The cutting forces in this parameter window are very small and in fact not measurable in our setup.

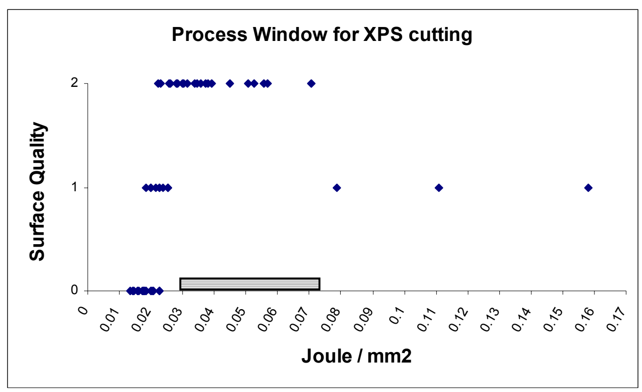

Figure 3: Cutting window. Quality level 0 is bad, 1 is moderate and 2 is good.

Problem description

From the described experimental results we found a process window in which 'good' surface quality can be produced, with one type of blade, cutting in a tangential direction. This is however not enough information for a proper control of the cutting process under all circumstances (figure 3). Apart from the surface quality it is necessary to be able to predict the exact position where the surface will be formed as a function of different process parameters. Therefore we must determine the offset of the produced surface from the centre

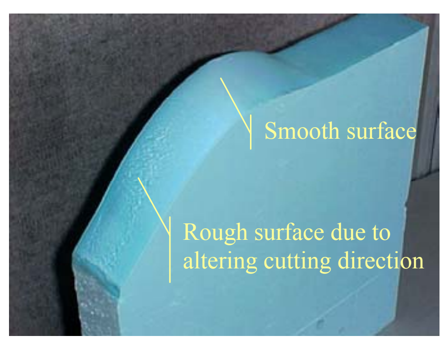

Figure 4: Cutting direction influence

line of the blade, under varying conditions. The first step in this is to find a formula that can predict the width of the produced gap during the cutting process. Second we must be able to control the surface quality under varying conditions. Apart from the thermal power and the cutting speed there is a need for more insight in the effects of the blade geometry and the cutting angle. In the earlier experiments we did not study the offset of the surface from the centre line of the blade. Further we also did not go into the thermal behavior of the blade during the cutting process.

Blade Geometry Influence

In this text we distinguish the blade geometry and the blade shape. We define the blade geometry as the shape of the cross section of the material because the blade is an extruded cross section. The blade geometry can for example be rectangular or circular. The blade shape is the global shape of the blade, due to the parameters that affect the blade. The blade shape can be straight or curved with non-, one- or more inflection points. In our earlier experiment we used a cutting blade that was specially made for foam cutting with a handheld tool. It is a Nickel-Chromium steel with a specific cross section shape which includes a cutting edge. (Figure 5) This material is normally used to create curved cutting blades with a fixed shape. It is not very well applicable for our purpose because we want to continuously change the blade curvature. One of the things that we learned from the first experiments was that optimal cutting happens virtually forceless as the foam material withdraws from the blade just before it is touched. This means that the stiffness of the blade, which was quite high for the original material, can be lowered considerably. The cross sections that we are going to examine will be rectangular without cutting edge because this is the best shape to make controlled bending of the blade possible. The width and height of the material will be varied in order to find the process influence of these values. The criteria for this optimal ratio are shape controllability and cutting performance. The Geometry influence is strongly related to the Cutting angle. Therefore a sequence of measurements must be designed to determine the influence of the separate parameters.

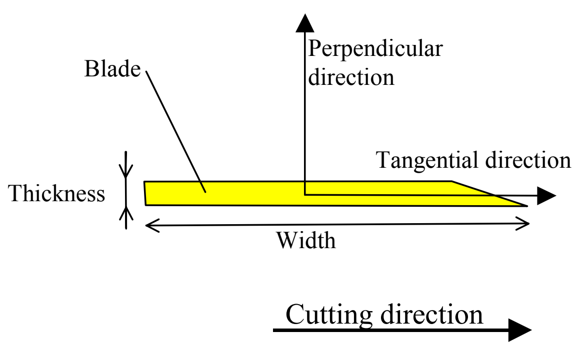

Figure 5. The geometry (cross section) of the original cutting blade

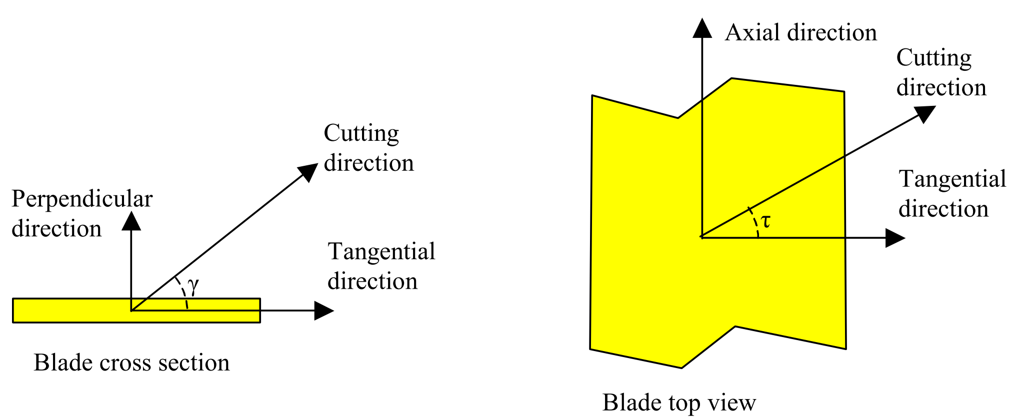

Figure 6: components of cutting direction

Cutting Angle
The FF-TLOM principle makes it impossible to create the needed surfaces by straight cuts only. When curved cuts have to be made and dynamically changing blade curvature is applied it is unavoidable that parts of the blade will cut through the material in a non-tangential direction. The cutting direction will usually have a tangential component, a perpendicular component and an axial component. (Figure 6)
A number of test cuts must be performed to determine the effect of these cutting-direction influences. From the results of these measurements we may be able to describe a virtual tool shape. This virtual tool should describe the area around the blade where foam is removed, using a certain thermal energy, speed and direction.

Surface offset
The surface that is produced by a cutting action usually has not touched the cutting blade. The blade has actually passed the surface at a distance. This distance, the surface offset, is expected to be dependent on the momentary process parameters. For a proper control of the produced surfaces we have to determine a model of the surface offset as a function of the relevant process parameters. Our experiments must be designed in such a way that we can derive such a model. The surface offset behavior is an important factor in the virtual tool description.
Our measuring approach starts with the assumption that the offset is symmetrical on both sides of the blade. In this case we can determine the offset by making two test-cuts with exactly the same process parameters, parallel to each other at a well know distance. The resulting piece of material must have a remaining thickness of the nominal thickness minus two times the offset distance. (Figure 7) This means that by performing the needed test cuts two times in stead of one, we will automatically have the necessary information on the offset behavior.

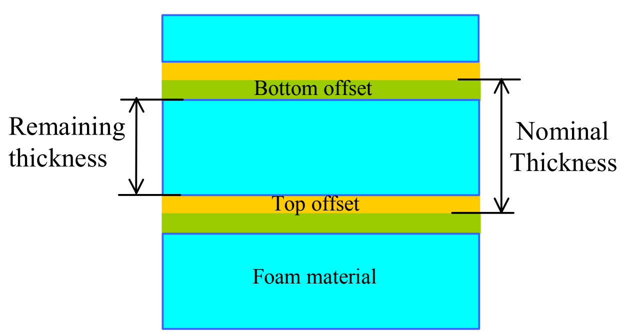

Figure 7: offset measurement

Blade temperature during cutting
Until this moment we do not know what the blade temperature is during cutting. We have seen in our first experiments that the cutting behavior changes during the cut. The resulting surface is different at the beginning of the cut than on the end of the cut. A reason for that can be a change in temperature during cutting, for example because some material does touch the blade and drains some thermal energy from it. To make this process better understandable and controllable we must measure the temperature of the blade during the cut. The temperature change may not be homogeneous along the blade, but can be different for the center of the foam and the edges of the foam. Therefore we will measure the temperature on several points, distributed over the blade. From the knowledge of the temperature behavior we may be able to conclude whether and how much extra energy must be added to the blade during a long cut.

Hypothesis

From our earlier experiments and from others research [1],[6], we expect the gap width that occurs when XPS is being cut with a heated blade depends on: 1) the used foam material, 2) the blade geometry, 3) the cutting angle γ, 4) the cutting angle τ, 5) the dissipated thermal power in Watt per mm. blade length P, and 6) the cutting speed in mm/sec V. In our earlier experiments a process window was found for the production of an acceptable surface quality, limited to one foam material and one blade geometry and with both the angles put to zero

The surface offset was only explored roughly. The goal of this research is to find an offset predicting formula for the cutting process. It is expected that this will make a better-defined process window necessary. However the main target is the offset control. We will try to create offset formulas for one type of foam material and a limited number of geometries. This means that the surface offset σ will be described as:

$\sigma_{geom.A} = F(\gamma, \tau, P, V)$

P/V influence

In our earlier experiments we combined the P and V parameter into one parameter Q, which represents the amount of thermal energy dissipated per square surface unit (Joule/mm^2). Evaluation of the surface quality in relation to this energy gave us a process window within which good surface quality was produced. At the start of our current experiments we will use the P and V parameters in combination; P/V. Our first hypothesis is that the offset is proportional with this value within the process window, which our area of interest. That means that the formula will contain a factor Q (= P/V).

Influence of angle τ

A change in the angle τ can be described as a change in the amount of dissipated thermal energy per surface unit. The change factor can be calculated from the change of the cutting length due to angle change. In figure 8 we see that the cutting part of the blade has a length a, witch is equal to the material thickness. If the blade is rotated over an angle τ the length of the cutting part of the blade is b, which can be calculated as b = a / cos τ. This means that the formula for surface offset will contain a factor 1/cos τ.

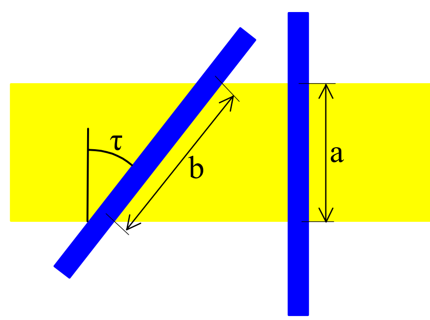

Figure 8: Influence of angle τ

Influence of angle γ

We expect that a change of γ from zero degrees will in some way influence the surface offset. The amount of offset increase must be experimentally determined. We do not know whether the influence is proportional or otherwise. Because the amount of thermal energy per surface unit is not changed the influence may be small. It could even be the case that only a change in surface quality is found. In our hypothesis for a formula we will use a factor (γb+1), in which b is a constant that has to be determined from our experimental results. When we combine the expected influences into one formula we find:

$$\sigma = a \cdot \frac{P}{V} \cdot \frac{1}{\cos\tau} \cdot (\gamma \cdot b + 1) + c$$

In this formula we expect that constants *a* and *c* are material related, while constant *b* should be blade geometry related. It is our aim to explore whether we can make this formula applicable for our process window.

The experimental set up

The experiments that we performed include only straight cuts, but with different blade orientations, and with different speed settings. In our earlier experiments we used a three axis milling machine as the moving machine for the cuts. This setup had some drawbacks, the most important was the problem that the axes are driven by stepper motors with a relatively course resolution. In the case of low speeds this means that the motion profile is not smooth but stepped. Further the length of the motions is limited, and in our earlier experiments we found that we would have to make longer cuts as many of the cutting processes in the first set of experiments seemed not to be stabilized at the end of the test piece. Thirdly we wanted to be able to orient the blade in a controlled manner. Therefore we implemented a set up with a servo driven linear axis that can travel 1000 mm. This axis can accurately be controlled in speed without stepper effect, and is used to move the material though the cutting tool. The material is fixed to the linear axis by a vacuum-gripping device. The cutting tool is a fixed blade holder that is attached to a six degrees of freedom robot arm. The robot is not moving during the cut, but is used between the cuts to position and orient the tool relative to the material (figure 9).

Figure 9: The used experimental set up

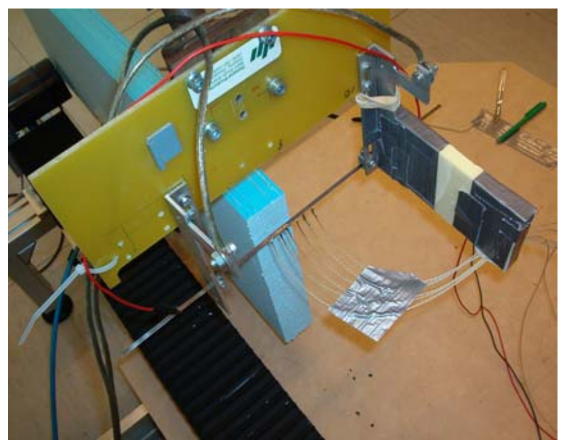

Figure 10: A blade fitted with temperature sensors

During the experiments three geometries, described by width * thickness, of stainless steel blades have been used: The C-type blade was used for a full set of measurements with angle, speed and power variations. A second blade with the C geometry was fitted with 6 temperature sensors (figure 10) and a subset of the first full set of measurements was performed to study the thermal behavior. With the P and Q geometries subsets and variants of the first full set were carried out in order to study the influence of different geometries. The foam material that was applied is Dow Styrofoam LB with a measured density of approximately 36 kg/m^3. The cutting length of the slabs was 800 mm. and the slabs where 50 mm. thick. The slices that were cut have a nominal thickness of 30 mm.

Blade type	Geometry
C	4 * 0.3 mm.
P	2 * 0.3 mm
Q	3 * 0.3 mm

Results

We produced an amount of about 100 test pieces, each under specified conditions. We used 3 blade geometries. One of the geometries was used in two sets of measurements, one without and one with added temperature sensors. By doing so we tried to have a good insight in the temperature behavior during the cutting process. From the produced pieces we could measure the produced gap width and observe the surface quality.

Measurement accuracy

In order to determine the effect of blade parameters on the produced gap width in the foam we measured the thickness of test parts. These parts are produced in two cuts, on for the top surface and one for the bottom surface (Figure 7). The thickness measurements were carried out with a slide gauge. A subset of the thickness measurements was repeated a number of times in order to find a value for the repeatability of the measuring method. We measured nine foam pieces each five times. In this cycles we found for one measurement point a maximum difference of 0.1 mm. The maximum standard deviation that we found was 0.04. We state that the repeatability of the physical measurement is 0.1 mm.

Experiment repeatability

It can be expected that the experiments that were carried out can only be reproduced with a limited accuracy. In order to find this repeatability we performed two types of repeatability tests. First we selected a number of experiments that were repeated in another measuring session, that means another day, equipment has been switched off and on again, another piece of foam material (We made sure that all the used foam material is from the same production batch). Second we took one specific measurement which was repeated a number of times during the same experiment session, so at the same day, in the same piece of material with all the equipment left in the same mode. In the first group of repeated experiments we found varying results. We can observe in the graph in figure 11 that the largest deviation between two repeated tests is 0.35 mm. This is the case between test C018 and C026. These are tests with the blade material that was tested the most extensive, and the experiments were distributed over several days. Verification in the experiment log learned that experiment C026 was performed at the beginning of the last session with this material. We found that that it was noticed that the blade was visibly corroded, as a result of the earlier cutting experiments. This is the only case where this observation was made. If we

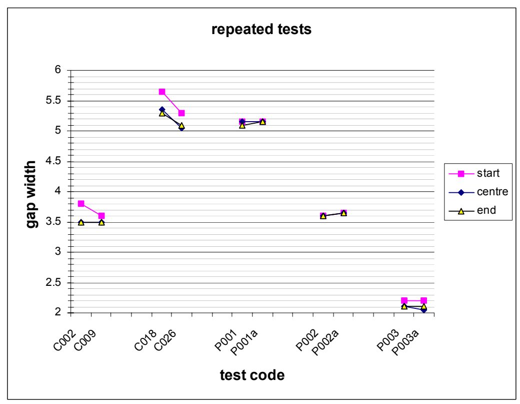

Figure 11: Tests repeated over different sessions. The first character in the code represents the Blade geometry used, varying angles and speeds were tested.

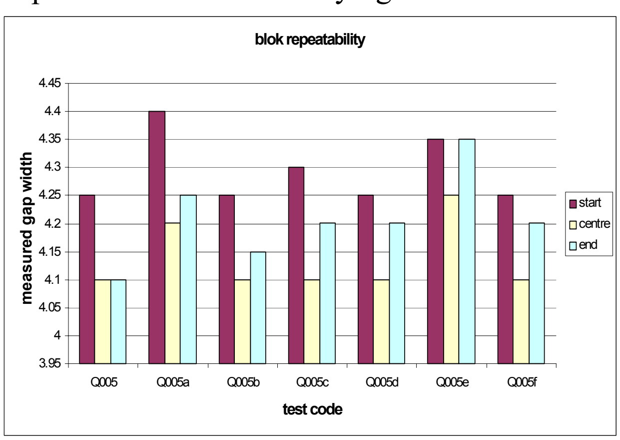

figure 12: Repeatability in one session. All tests used the Q geometry and constant speed and angle settings.

assume that this may have influenced the experiment significantly and therefore leave this case out we are left with a surprisingly good repeatability. There is one case left where at the start of the cut the deviation is 0.2 mm., in all other cases it is better than 0.1 mm. which was found as the actual measurement accuracy

In the second repeatability test (Figure 12) we repeated a test 7 times in a row, we found values that are in a comparable magnitude. The maximum difference found there is 0.25 mm. In this group, test Q005e has the highest deviation. If we leave this measurement out the maximum difference found is limited to 0.15 mm.. We state that the repeatability of the experiments overall is better than 0.25 mm.

Power distribution over the blade during the cutting process.

During the experiments it proved to be difficult to control the cutting parameters in an accurate manner. Being a process that is determined by the added amount of thermal energy it is crucial to be able to control this amount as precise as possible. One of the problems is that the dissipated power may be influenced by the actual cutting process itself. If we observe a graph of the blade temperature during a cutting action we find that the blade temperature is decreasing considerably in the piece of the blade that is passing through the foam material. We know that the specific resistance of a metal depends on the temperature of that material. During the experiments we observed that the current that is consumed by the blade typically increases during the cut. This is understandable if we consider that the resistance of the blade decreases when the material is cooled down, and that the current is generated by a poorly stabilized power source. In order to determine the influence of this effect we studied a specific case: During a cutting test T002 we logged the temperature of the blade and the consumed current through the blade. (Figure 13) The length of the blade is 175 mm. We find that the temperature of the centre of the blade starts at 580 degrees Celsius, before the cut, and drops to 440 degrees Celsius during the cut. A thermocouple that is mounted just outside the cutting part of the blade shows virtually no temperature drop. We logged the current and overall voltage during the cut and found that the resistance of the blade is158.8 $\cdot 10^{-3}$ Ohm before the cut and 155 $\cdot 10^{-3}$ Ohm during the cut. That means that the resistance decreased by 3.8 $\cdot 10^{-3}$ Ohm. As mentioned the total length of the blade is 175 mm., while the cutting part of the blade is limited to 50 mm. Because the temperature is virtually not influenced outside the cutting part, we can assume that the change in resistance takes place in the cutting part of the material. The resistance of that part was (50 * 158.8)/175 = 45.37 $\cdot 10^{-3}$ Ohm. The resistance during the cut is than 45.37 – 3.8 = 41.57 $\cdot 10^{-3}$ Ohm. With the measured current of 19.65 A before the cut and 20.0 A during the cut this results in a dissipated power in the cutting part of the blade of 17.52Watt before the cut and 16.63 Watt during the cut. That means that the power dissipation in the cutting part of the foam has dropped 5% during the cut, caused by the cooling of the blade. This is a considerable amount that has to be taken into account when a dedicated control device for the cutting power is implemented. For this paper we assume that the effect is working in all the executed tests in a comparable manner. This means that all the measured power values should have an offset of about 5 %. For the principles of the process this doesn't make a large difference.

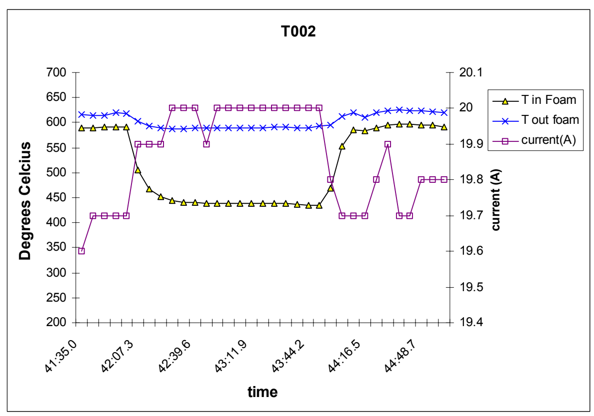

Figure 13: Thermal behavior of the blade during a cutting experiment.

Analysis

Influence of power per square unit

We performed a number of tangential cutting experiments with different blade geometries and power/speed combinations. When the resulting gap measurements are combined we find a graph in which we clearly observe a linear relation between the amount of dissipated thermal energy per square surface unit and the produced gap width (figure 14). Neither the geometry that is applied nor the actual blade temperature is of any influence on the gap. From the graph we can find that in our formula:

$$\sigma = a \cdot \frac{P}{V} \cdot \frac{1}{\cos\tau} \cdot (\gamma \cdot b + 1) + c$$

The constant *a* is 74.843 and the constant *c* is –0.2868

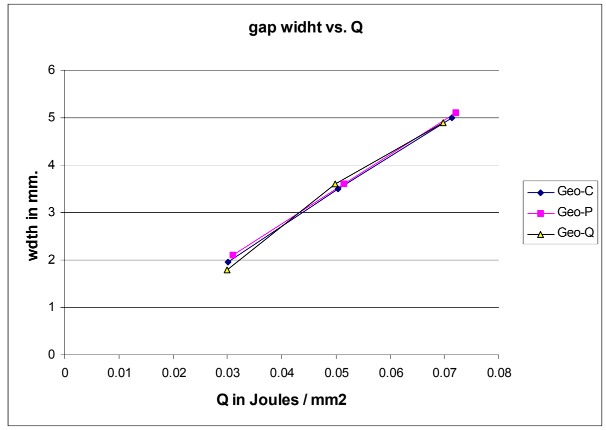

Figure 14: The gap width as a function of dissipated power for different blade geometries

Influence of the angle τ

As explained before a change in the angle τ can be described as a change in the amount of power per square surface unit. We did two experiments to verify this behavior. First we varied the angle τ without any speed compensation. And measured the resulting graph. Figure 15 shows the graph. Then we applied comparable τ variations but compensated the speed by multiplying it with the factor $\frac{1}{\cos\tau}$. This resulted in the second curve shown in figure 15.

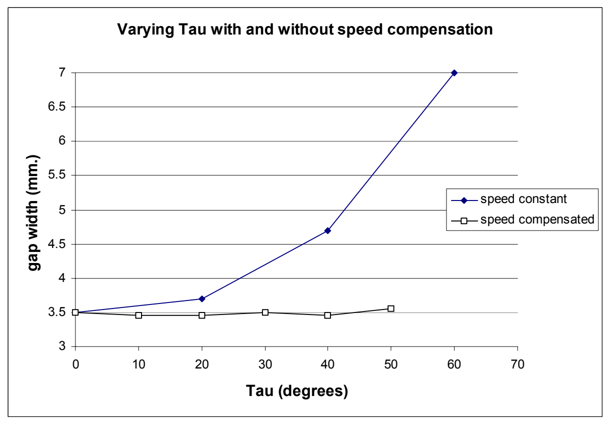

Figure 15: Influence of angle τ on the gap width

From the graphs we conclude that our hypothesis on the influence of angle τ is correct.

Influence of the angle γ

We performed two sequences of experiments with varying γ and constant power dissipation. The first sequence used blade geometry C and the second used blade geometry P. Figure 16 shows the graph of the resulting gap widths. It is observable that both the graphs are horizontal with small deviations until a certain point. For The C geometry this point comes sooner than for the P geometry. The reason is that at this point the cutting process is no longer stable. The blade is touching the foam and a force is building up. The blade is pushed away, the force increases

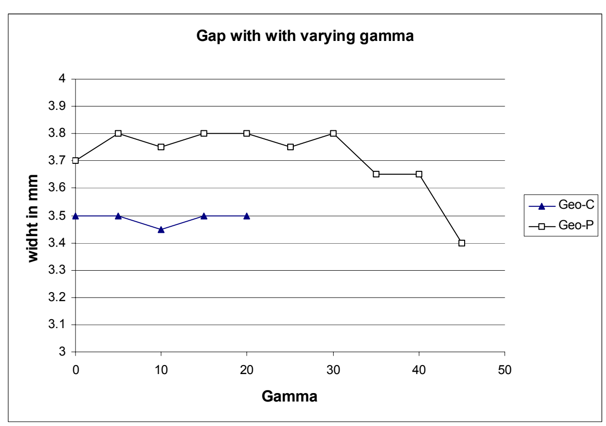

Figure 16: Influence of Angle γ on the gap width

further and the cut is no longer controllable. The observation that the two curves in the graph are about 0.25 mm. apart is explained by a slight difference in applied power. If a correction for the power dissipation is made they fit well together. The conclusion from this graph is that the angle γ has no influence on the gap width, up to a point where the cutting process becomes unstable. This point is earlier reached with a wider blade (the C geometry). Therefore the factor *b* in the formula is found to be zero.

Asymmetry in the gap width

Although the gap width is not influenced by the angle gamma, there is another effect that should be mentioned. During the experiment we observed that the offset of the surface from the centre line of the blade is not symmetrically distributed when the blade is cutting with a gamma angle. Further we observed that the surface quality differs significantly depending on this gamma angle. In figure 17 we can see that with the given blade angle and cutting direction the offset above the blade (Top offset) is larger than below the blade (bottom offset).

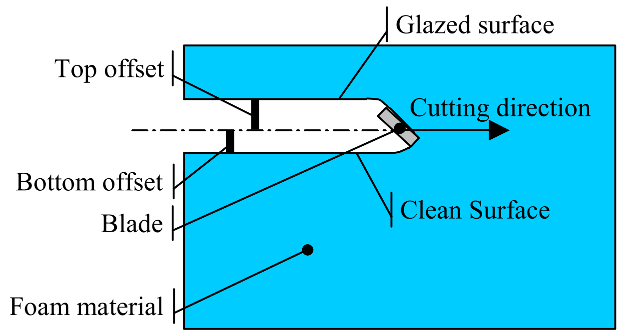

Figure 17: Effects of a cut made with an angle γ of the blade

Further it is marked that the surface above the blade has a glazed quality, which is not optimal for our purpose, while the surface below the blade is a clean high quality surface. If we invert the cutting direction in this picture we find that the offsets and surface qualities also swap to their opposites. In order to find more about the offset asymmetry we performed some tests with varying cutting directions. We defined the direction that was used for the majority of the measurements as the Normal direction, while the opposite direction is called Reverse direction. With each blade geometry we cut four test pieces, all with a γ of 30 degrees, but with all possible combinations of normal and reverse cutting directions. From the graph in figure 18 we can conclude that there are only small differences between the NN and RR combination, namely maximum 0.15 mm. We expect them to be the same because it is in fact a repeated test, which is only performed in opposite direction. De 0.15 deviation is within the repeatability margins. The RN and NR combination show large differences, which is again expected because one of the two combines two large offsets and the other combines two small offsets. We found for the C geometry a large offset of 116% of the average, for the Q geometry we found a large offset of 117% of the average offset and for the P geometry we found a large offset of 108% of the average. The used power dissipation is not the same for the different geometries. From this can we can conclude that there is indeed a significant asymmetry in the offset when a γ angle is used. We cannot yet predict this offsets in an accurate manner. Some extra cutting tests must be carried out to collect the needed data for that.

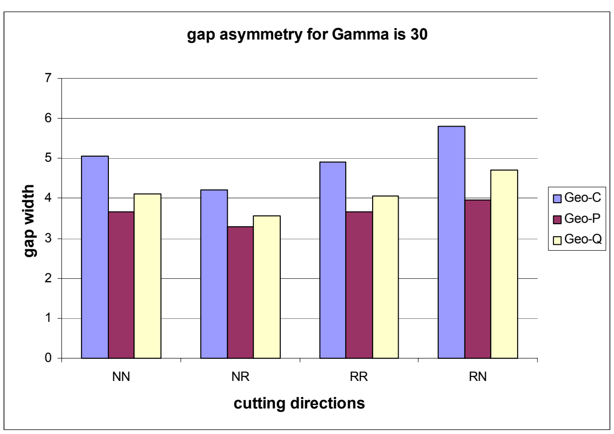

Figure 18: calculated gap width for different combinations of cutting directions

Conclusions

The formula that we created in our hypothesis has been tested and found to be correct. For the constants *a* and *c* we found applicable values, the constant *b* proved to be zero. The resulting formula is therefore:

$$\sigma = (74.843 \cdot \frac{P}{V} \cdot \frac{1}{\cos\tau}) - 0.2868$$

It was found that it is crucial to have a precise control on the dissipated power in the blade. This is difficult, as the cutting process itself is influencing the amount of dissipated energy in the blade.

We observed that when an angle γ is applied, the gap that is created is not symmetrical, seen from the centre line of the blade. More experiments are needed to determine a formula that predicts this asymmetry. In our experiments we found differences from 108% to 117% between the average offset and the largest offset in an asymmetric case with angles γ f 30 degrees.

Finally it was found that the asymmetric gaps that are created when an angle γ is applied also have different quality levels on the two opposite sides of the gap. This is an important finding in relation to the cutting strategy that should be followed in order to create optimal models.

References

[1] Ahn, D.G.. Lee, S.H., and Yang, D.Y., Investigation into thermal characteristics of linear hotwired cutting system for variable lamination manufacturing (VLM) process by using expandable polystyrene foam, International Journal of Machine Tools & Manufacture 42 (2002) 427-439.

[2] Hope, R.L., Jacobs, P.A., and Roth, R.N., (1997), Rapid Prototyping with Sloping Surfaces, Rapid Prototyping Journal 3-1, pp. 12-19

[3] Horváth, I., Broek, J.J., Lennings, A.F., and Vergeest, J.S.M., Reshapeable Concept Models by FF-TLOM: A True Alternative of Conventional Clay Modeling, ISATA'99, paper 99ME069

[4] Horváth, I., Vergeest, J.S.M., Rusák, Z. & Broek, J.J., Application of Editable Physical Concept Models in Industrial Design Engineering, on the 26th International Conference on Computers & Industrial Engineering, Melbourne, Australia,

[5] de Jager, P.J., (1998), "Development of a New Slicing Methodology to Improve Layered Manufacturing", Ph.D. thesis, Delft University of Technology, pp. 129.

[6] de Smit, A., Broek, J.J., and Horváth, I., (1999b), Experimental Investigation of Factors Influential for the Flexible Blade Based Prototyping Process, Proceedings of the 1999 ASME Design Engineering Technical Conference, paper DETC99/DFM-8960.

[7] Viswanathan, A., Jouaneh, M., Datseris, P. and Palm, W.J., 1996, "A Manufacturing System for Automated Production of Polystyrene Molds", IEEE Robotics & Automation Magazine, Vol 3, Number 3, Sept. 1996, pp. 39-43.