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Direct Wire-Tension Measurement Based Bowing Correction in Hot Wire Cutting of Polystyrene

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Abstract

The accuracy of parts produced by hot wire cutting of expanded polystyrene (EPS) is severely affected by bowing of the wire. The degree of bowing depends on the current supplied and the feed rate of the hot wire. Bowing occurs when the current is insufficient to melt the foam ahead of the wire and the mechanical interaction between the foam and the wire increases. This causes an increase in the tension in the wire and this is directly measured using a load cell arrangement. Based on this direct wire tension measurement a real time closed-loop feedback mechanism is implemented which regulates the current to maintain a constant wire tension and eliminates the bowing of the hot wire during the cutting process. For a particular feed rate the feedback mechanism precisely fine tunes the current supplied to the wire such that there is no mechanical drag force between the foam and the wire. The sensitivity of the feedback mechanism is high and responds to very minute contact between the foam and the wire and nominally regulates the current variation in the hot wire, hence, maintaining a constant kerf width throughout the cut. This mechanism allows to significantly improve the accuracy of the EPS part even in complex 3D cutting paths.

Keywords: Hot wire cutting; Feedback mechanism; EPS; Bowing; Wire tension

1. Introduction

One of the popular ways to make complex shapes using soft materials like expanded polystyrene (EPS), extruded polystyrene (XPS), rubber and wax is by Laminated Object Manufacturing (LOM) where the individual layers are made using the hot wire cutting (HWC) technique. The HWC uses a heated Nichrome (NiCr) wire to cut and sculpt the soft materials. HWC, in combination with LOM or by itself, is used to manufacture prototypes for the entertainment industry, metal casting foundry, packaging industry, and construction industry.

The NiCr wire used in the hot wire cutting process has a characteristically high resistivity and high melting point. This properties of NiCr allows it to reach a sufficiently high operating temperature by the principle of Joule heating when current is passed through the wire. This enables the NiCr wire to melt and ablate polymers with low melting point. Among the polymers, EPS being cheap and easily procurable, is a commonly used workpiece material in the HWC process. In this cutting process, the workpiece is placed transversely along the stroke length of the current carrying hot wire. The wire is hinged at both ends and fed into the EPS block to produce the desired shape of EPS. This process was initially used to produce simple parts that can be manufactured by guiding the wire. Complex shapes require the wire to be moved in multiple axes by a computer numerical controlled (CNC) system (Vishwanathan et al. [1]). Currently, both small and large life-size shaped prototypes are widely made using the HWC process as they are both cost effective and easy to manufacture. This technique is commonly used to manufacture various complex EPS shapes for the entertainment industry, metal casting foundry, packaging industry and construction industry. The metal casting foundries uses complex-shaped EPS patterns in the lost foam casting process; EPS volatilizes when it encounters the hot molten metal melt-front. Precision of the

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EPS pattern is important here to control the cast part dimensions. It is also a common requirement of the packaging industry for precise prototypes of EPS since unless it snugly envelopes the parts at critical junctions, its shock absorbing quality cannot be used effectively during transportation of fragile commodity. EPS prototypes are also commonly used in entertainment, architecture, and construction industries as insulators and shape providers where reasonable precision of shape is expected.

The accuracy and the precision of the prototype produced in the HWC process hinges over two crucial parameters viz. the amount of current supplied to the wire and the feed rate of the wire. Poor control and noise results in fluctuation in wire temperature and wire tension which culminate in changes in the kerf width and can also result in bowing of the hot wire. Due to these reasons, the repeatability of the foam cutting process is often low and the accuracy of the prototype is similarly subpar. Closely controlling and optimizing the interplay between these two parameters can produce very accurate prototypes [2] . Such optimization processes when done by manual tuning can be time consuming and can vary from machine to machine. Therefore, to cut intricate shapes robots were introduced to the hot wire cutting of EPS. Hamade et al. [3] developed a subtractive 5-axis robotic arm control software Modelangelo, using feedback mechanism to correct the tool position. In a recent study, Rust et al. [4] also used multi-axis robot to create complex shapes for architectural applications. Further, Kim et al. [5] developed a hot rotary tool which can be used to cut the foam with good surface finish.

For producing a critically accurate prototype it is important that the kerf width is predicted accurately. For prediction of kerf width Ahn et al. in 2002 [6] investigated the thermal effects of the hot wire. Considering the hot wire cutting process analogous to laser cutting and welding processes, they predicted the kerf width and determined the optimum cutting conditions. In 2003, Ahn et al. [7][7] further investigated the variation of kerf width while making angular cuts. More work was carried out in 2012 by Brooks et al. [8] to predict the kerf width using nonlinear transient thermal model after experimentally determining the melting point of the foam. A numerical model was also developed by Petkov et al. in 2016 [9] which used a thermo-electo-mechanically coupled model to determine the kerf width after determining the temperature profile of the wire. This model was also applied to a double curved blade to determine the temperature in the blade and hence the kerf width produced [10]. In another recent work by Kim et al. [5] the kerf width produced by the rotary tool was also numerically predicted and compared with the experimental results.

The hot wire cutting of the foam begins with providing a predetermined current and feed rate to the hot wire such that the wire temperature is sufficient to melt the foam ahead of the wire and the feed rate is less than the ablation rate of the foam. But as the cutting begins the wire temperature drops due to the heat utilized in melting the foam and the time required to melt the foam increases, increasing the wire-EPS interaction and hence the drag force. Therefore, it is important to understand and quantify the drag force and its variation with the process parameters. Atchison and Brooks et al. ([2] [11]) studied and reported the mechanical wire EPS interactions and suggested that for smooth cutting and less surface roughness the temperature in the wire must be just sufficient such that there is a balance between thermal and mechanical cutting of the foam. The volumetric specific heat input was used to link the force of interaction and the heat input with the kerf width by Aitchison et al. [2] to determine the optimum cutting condition. Further, the temperature drops in the hot wire as cutting proceeds was related to the force of interaction between the foam. Also, the barrelling of the cut profile due to the difference in the wire temperature along its length was also explained [2] . In both [2] and [11], the force of wire-EPS interaction was measured by mounting the entire wire holder at its bottom on a load cell. Based on this force measurement and the temperature drop a feedback mechanism was designed to maintain a constant (average) wire temperature (measured by a thermocouple arrangement) by increasing the current supply in the wire. However, the method does not use real-time measurements of force but an empirical relation based on forces measured a priori. Moreover, it is important to note that the currents used in this arrangement is high, where the mechanical EPS-wire interactions are usually minimal. More current leads to higher melting/kerf width and higher loss of material. Hence, it is not clear if the reported system and controls would work for minimal current setting commonly used to keep kerf-widths low and where mechanical interactions could be high. In addition, during low current operation, the method of mounting of the load cell to measure the mechanical interaction of wire-EPS via force measurement is critical. Mounting the load cell at the bottom of the wire holder has several disadvantages [11][11][11][11]. Force measurement made at the bottom of the wire holder is farther away from the actual EPS-wire interaction zone. Measuring the wire-EPS interactions closer to the zone of interaction would be better.

We build on top of the work reported by [11] and provide a significant improvement over their method. While the setup used by Brooks and Aitchison (2010) [11] measures cutting force by mounting the wire holder on a load cell, we report wire tension measurement by directly linking a special-purpose load cell to the wire itself. This provides two advantages (a) the measurement is more sensitive to small changes that the wire encounters during cut (b) the force feedback works in three dimensional cutting paths without any addition to the setup. The present work thus implements a method to measure wire tension directly during hot wire cutting of EPS and also presents a feedback mechanism which controls the current supplied to the wire based on the real time interaction between the foam and the wire during the cutting process. The feedback mechanism operates by detecting, in-process live, the tension in the wire and maintains a constant wire tension throughout the cutting process. In this way, irrespective of the variation of temperature in the wire the feedback mechanism responds to any drop in the temperature in the wire which is traced by the change in the tension in the wire. Further, to overcome the deleterious effect like bowing of the hot wire, the closed loop feedback mechanism is designed such that the error between the desired and the actual prototype is minimized during the machining process. Optimization of the initial tension in the wire is also performed in the present work considering the thermal expansion at various current levels. Thereafter, developing a force feedback mechanism which can eliminate bowing keeping tension constant and regulating current in the hot wire.

2. Experimental arrangement for wire-tension measurement

An in-house developed CNC controlled hot wire cutting machine (Figure 1) has been modified in this study. This setup uses a NiCr wire as tool to melt and cut foam materials via Joule heating. The machine is built with rigid aluminum extruded frames. A stepper motor with driven teeth pulley is fixed to a set of two vertical steel plates at both ends of the wire. This pulley drives a timer belt of same pitch to move the axis on linear motion guided rails. The vertical plates are fixed to the movable linear drive which holds the NiCr wire tool with the help of tensioned springs and roller supports at the two ends of the wire. The machine is synchronized along both X and Y axis. MultiCNC CAM software is used to control the motion and direction of the motor.

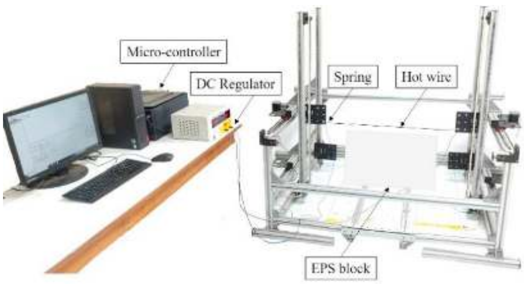

Figure 1. In-house built CNC hot wire cutting system.

The system has been modified a load cell Sensit™ LM200 is powered is attached in between the NiCr wire and vertical plate as shown in the Figure 2 to measure the tension in the hot wire at a rate of 50 samples per second. Feedback control is established through a micro-controller (Arduino Uno) which received input from the load cell and alters the current going into the NiCr wire.

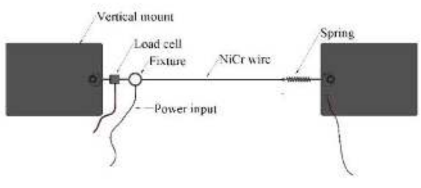

Figure 2. Schematic showing the load cell attached directly to the wire for tension measurement. The current connection is made after the load cell so that the load cell is not affected by the Joule heating effect.

All experiments were performed on 800 x 200 x 200 mm^3 EPS block cut using a 1000 mm long NiCr wire of 28 gauge diameter.

3. Bowing and Wire tension of the hot wire

3.1. Bowing of the hot wire

As the block is placed in the within stroke length of the wire. The wire is supplied with current and a feed rate to sculpt the foam in a prescribed shape. As the cutting begins the wire proceeds by melting and ablating the foam ahead of it. During the cutting process, if the feed rate is higher than the ablation rate of the foam or the current (wire temperature) is lower than the melting point of the foam, the wire comes in physical contact with the foam. When there is a physical contact between the foam and the wire, the cutting becomes difficult as it takes more time for the wire to melt and ablate the foam. Under these circumstances, as the wire hinged at both ends, continues to travel at the same feed rate the center portion of the wire lags as compared to its ends. Hence, forming a bow shape. This is the bowing phenomenon of the hot wire. This is an unfavorable phenomenon and can be very severe while cutting large prototypes [12]. Further, during this process, the springs attached at the hinge points extends indicating a rise in the wire tension. Such a phenomenon can lead to very inaccurate prototypes and it must be eliminated from the cutting process.

3.2. Initial wire tension and wire bowing

When the wire begins the cutting process, it is important to optimize the tension in the wire. This is because a low wire tension (sagging wire) will result in a higher bowing and a high wire tension will tend to snap off the hot wire even with slight contact with the foam. Therefore, it is important to optimally set the value of wire tension before the cutting process begins. Further as the current is supplied to the wire the wire expands almost linearly with temperature. Hence the wire must be tied such that the tension in the wire after turning on the current supply is optimum.

So, the initial tension in the wire was optimized such that the bowing of the wire is minimum. The EPS block was cut at current of 1.5 A, 1.8 A and 2 A at a constant feed rate of 500 mm/min. Similarly, the EPS block was cut at a feed rate of 250 mm/min, 500 mm/min and 750 mm/min at a constant current of 2 A. In these conditions the bowing in the wire was minimum at a tension of 25 N.

After setting the initial tension in the wire as 25 N (after turning on the power supply) the bowing of the wire at various feed rate was measured using camera imaging at the wire exit (see [12] for details) as shown in Figure 3. Higher the current, lower the wire deflection, but higher the kerf loss. Hence, the main goal is to minimize these wire deflections even at low current values, where kerf loss is minimal.

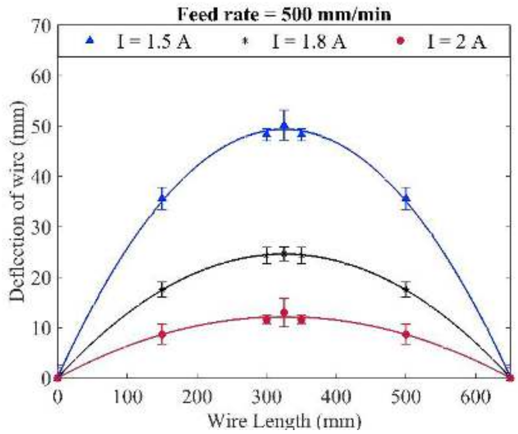

Figure 3. Wire bowing measured as deflection of the wire at various currents. The goal is to reduce this bowing effect to improve accuracy of cut.

3.3. Wire tension during cuts

The variation in the wire tension at various feed rates is shown in Figure 4. At very low feed rates the wire tension is constant throughout the cut. At higher feed rates the tension is seen to almost continuously increase until the wire exits the EPS block upon which the tension drops. Wire-tension variation for various current values and at a constant feed rate of 500 mm/min is shown in Figure 5. It is evident that, as bowing in the wire increases the tension in the wire increases. The maximum tension in the wire was reported as 27 N at a feed rate of 750 mm/min and 1.8 A for a bowing of 62 mm.

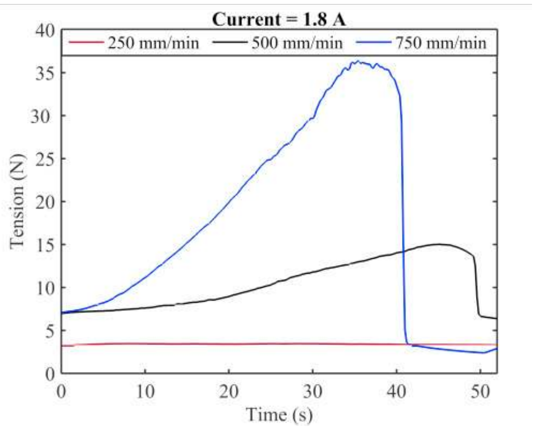

Figure 4. Variation in wire tension, at a current value of 1.8 A for various feed-rates, as a function of time of cut from start of cut to complete exit of the wire out of the EPS block

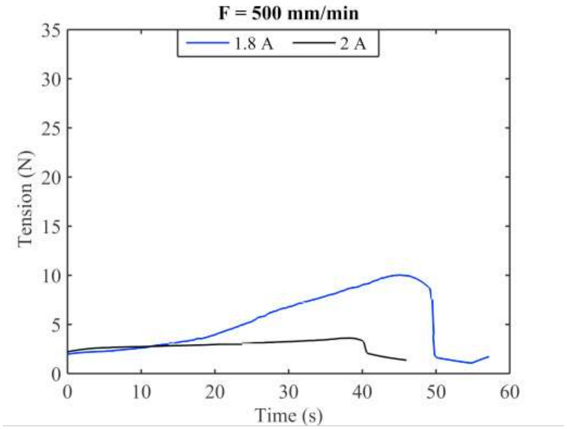

Figure 5. Variation in wire tension, for various currents, as a function of time of cut from start of cut to complete exit of the wire out of the EPS block

4. Feedback control using wire-tension

4.1 Design of the feedback system

The hot wire cutting process is used to sculpt very complex shapes of EPS. The bowing of the hot wire during the cutting process can limit the ability of the machine to produce accurate intricate shapes. This is because even with small amount of bowing in the wire it becomes impossible to produce even simple sharp edges. All sharp edges are filleted. Further, this inaccuracy is very severe while making a 3D profile. Therefore, it becomes very important that even small amount of bowing in the wire is removed. Although, slower feed rates and higher currents can reduce bowing, but this can result in slow production time (at small feed rates) or high kerf width loss (at larger currents). Also, sometimes despite choosing optimal cutting parameters, during machining the parameters can vary depending on the temperature drop in the wire during the cutting process, wire-EPS interaction, material type, density and moisture content in the foam. Hence it becomes very tedious for the process planner to optimize the cutting parameters. A real time feed-back mechanism based on live measurement of wire tension can help solve this problem and is developed here. Such a mechanism can capture all the dynamic changes occurring during the cutting process and allows choosing the optical current value (at a given feed date) that minimizes bowing effects. Hence, in this work a force feedback system is developed which regulates the current supplied to the hot wire based on minute variations in the wire tension.

The wire is always kept in tension at the optimized initial tension value and this initial tension in the wire is set to zero. This meaning that the control system deals with tension value over and above this. The load cell is initially excited by supplying a 5 V DC power and the output signals of the load cell is recorded. As cutting begins the fluctuation in the load is calculated by measuring the potential difference between output signals. During experiments, it is seen that with a variation of 1 N force the voltage fluctuates by 0.1 mV. Such a small variation makes it difficult to predict minute tension variation in the wire during cutting. Hence, a differential amplification is done by using an amplifier (AD620) which amplifies the voltage by 100 times. This amplifier is also used to convert the double output signal of the load cell into a single output. The digital Pulse Width Modulation (PWM) output from the micro-controller (Arduino UNO) is given to the N-channel MOSFET to amplify the signal of 5 V upto output to a voltage of 20-40 V. At this range of voltage, the change in wire tension can be easily used to regulate the current supplied to the wire and depict even small fluctuation (<1 N) in the wire tension. The flow diagram and the circuit of the feedback loop is as shown in Figure 6(a) and (b) respectively.

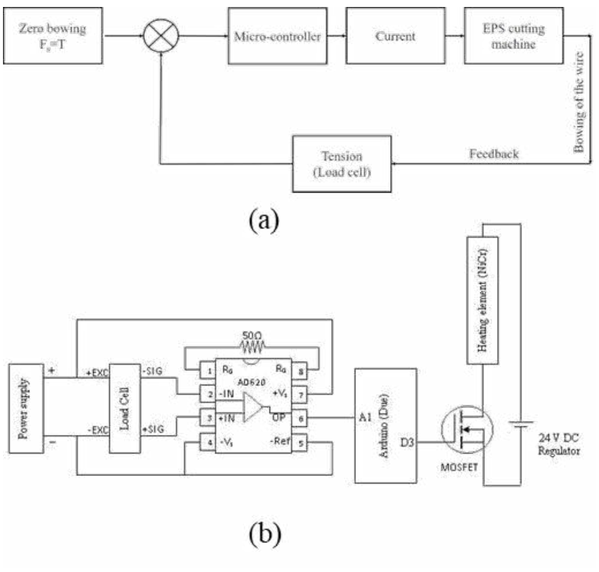

Figure 6 (a) Control block diagram of the wire-tension based feedback control developed (b)

To design a proportionate feedback mechanism, the differential current required to be supplied to the wire based on the analog value read by the microcontroller is determined experimentally by manual tuning. Based on this a linear relationship between the duty cycle and load variation from the initial set value is established as shown in Figure 7. Depending upon the application of the feedback mechanism a non-return proportionate algorithm is used in this work. Such a mechanism implies that as the current increases with an increase in wire tension, the elevated wire current is maintained throughout the cut and any further fluctuation in the wire tension is added to the existing current. This non-return algorithm restricts bowing accumulation and hence such an algorithm will always require very minute current regulation

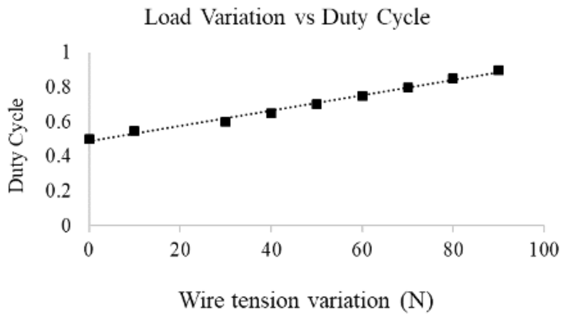

Figure 7. Establishing relation between duty cycle and wire tension variation

The amount of current to be supplied to the wire for a particular increase in wire tension is determined by manual tuning. Manual tuning was performed as follows: at very low feed rates the wire was moved forward towards the EPS block at an initial nominal tension and nominal current, until a certain increment in wire tension was obtained. The current was then increased until the wire tension fell back to its nominal value. The wire was then again moved until a higher wire tension is obtained; and then, again the current required to bring it back to nominal was noted. In this manner Figure 8 was obtained. These values are then used to determine the relationship between the wire tension and the wire and fed to the microcontroller. A linear approximation is established between them as shown in Figure 8.

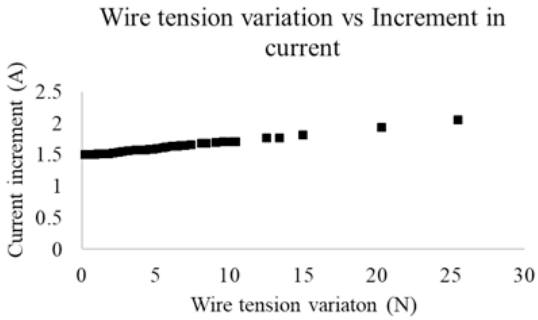

Figure 8. The increment in current to be supplied to the wire for a particular increase in wire tension is determined by manually tuning the controller.

It is to be noted that Figure 8 is independent of wire feed rate as it was obtained quasi-statically. The data and relationship of Figure 8 is applicable even at higher feed rates - it is just that the controller must respond faster at higher feed rates as per this linear relationship. We do note here that different data such as in Figure 8 needs to be obtained for various densities of EPS and of course for other materials that use the hot wire cutting process.

4.2 Process performance with feedback system implemented

When the cutting is carried out without a feedback mechanism the current supplied to the wire is constant, but the wire tension keeps on increasing as the foam and wire interaction increases (Figure 9). Further while cutting with feedback mechanism the current supplied to the wire is increases to compensate for any variation in the wire tension such that the tension remains constant throughout the cut (Figure 10).

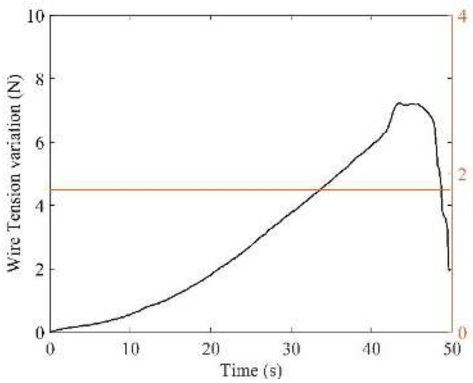

Figure 9. Current and wire tension variation with cut time, when feedback control is *not* in operation. Note that current is constant and wire tension continues to raise as the cut proceeds.

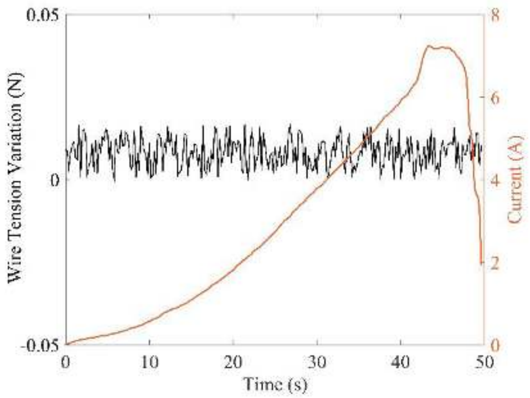

Figure 10. Current and wire tension variation with cut time, when feedback control is in operation Note the tension variation in a very small range of less than 0.02 N, while current increases to manage the bowing.

During the cutting process, the controller can detect a variation of 0.1 N in wire tension and minutely increase current proportionately (0.1 mV for 1 N) such that the wire tension remains constant throughout the cut making the feedback system highly sensitive. As cutting begins and the wire begins to bow, this bowing of the wire accumulates to become more severe as cutting proceeds. Therefore, it is important to control bowing at its early stage. The high sensitive of the feedback system hence helps in controlling the bowing at a very early stage with minor current regulation. This allows the kerf width to remain almost constant throughout the cutting process even with the feedback mechanism.

To verify the efficiency of the feedback mechanism the initial current and feed rate is set such that there is a definite wire bows and a ‘z shape’ prototype is cut. When the prototype was cut without the feedback the sharp edges of the ‘z shape’ prototype could not be produced and instead a fillet was produced which is highly undesirable as shown in Figure 11(a). When the feedback algorithm is fed to the microcontroller and the cutting is carried out with the same initial conditions, the hot wire manages to cut a sharp ‘z shape’ with well-defined edges as shown in Figure 11(b).

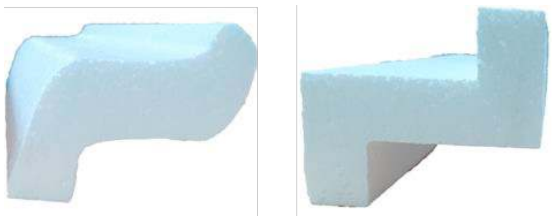

Figure 11. Actual shaped cuts made on EPS (a) without wire-tension based feedback and (b) with wire-tension based feedback

The variation of kerf width with and without feedback is compared at various feed rate and current as shown in Table 1. There is little change in kerf width with the implementation of wire-tension based control. This is because the overall average current remains more or less the same – this can be verified by comparing Figure 9 and Figure 10. Hence, without causing bowing the feedback control has managed to complete the cutting process. The issue of controlling the kerf width would require a separate process of minimizing the average current and its variation around this average to cause minimal bowing. This would require a more complex control, something which is being planned next.

Table 1. Kerf width comparison with and without wire-tension based feedback.

Feed rate = 500 mm/min				
Current (A)	Bowing (mm)	Tension (N)	Kerf width without feedback (mm)	Kerf width with feedback (mm)
1.5	50.15	13.5	0.36	0.37
1.8	24.633	7	0.41	0.4
2	12.988	1.22	0.56	0.56
2.2	4.36	0.8	0.81	0.83

4. Discussion

The closed loop feedback mechanism discussed in the present work measures tension with the help of load cell which is directly attached to the wire. As the cutting begins, the wire experiences some vibration from the motors and other noises. These noise is well captured when the load cell is attached to the wire. Further, this technique does not relate the tension in the wire to the wire temperature and it directly monitors change in the wire tension and regulates the current accordingly. Hence, this technique can be implemented without the need for additional temperature sensors. This technique is independent of the work piece size. Both large and small work pieces can be accurately shaped, and the bowing of the wire can be eliminated even while executing complex 3D cutting paths.

5. Conclusion

The wire-EPS mechanical interaction can be directly measured by detecting wire-tension in-situ during the hot-wire cutting process. A closed feedback control incorporating such a measurement can be used to adjust the current to keep wire tension constant. The main conclusions from this work are:

- Wire tension is seen to increase as the cut proceeds at a constant current value. Wire tension is low at small feed rates and high currents.
- The feedback mechanism detects minor changes in the wire tension with the help of load cell arrangement and regulates the current to control bowing at its initial occurrence.
- Precise three-dimensional cuts, without wire bowing or lag, is possible with this arrangement of force measurement; this has been effectively demonstrated.
- This feedback system is seen to be highly sensitive to minute fluctuations in the wire tension and responds to small load change and does not affect the kerf width.

Hence implementation of this mechanism can help in building precise EPS shapes with increased flexibility in operating parameters.

Acknowledgements

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