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PC-BASED LOW-COST CNC AUTOMATION OF PLASMA PROFILE CUTTING OF PIPES

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ABSTRACT

In modern fabrication shops, it is important to invest in affordable, state-of-the-art technology; including material handling systems, computerized motion control, advanced cutting systems and dedicated software programs in order to compete effectively in the market. In pipe profile cutting operations using plasma arc, CNC automation introduces higher precision, repeatability and speed. One method of simplifying the automation and hence improving the profit margins is the reduction of the number of controlled axes. Further by simplifying the design, the CNC machine is made more compliant to the technique of error modeling and compensation. This research investigated the suitability of a PC-based CNC pipe cutting machine by simultaneous control of only two axes. The developed machine competes well with similar machines having higher number of axes. The shortcomings arising from such simplification of the machine and the plasma arc cutting (PAC) process in general; are pointed out and possible improvements suggested.

Keywords: pipes, cutting, plasma, arc, low-cost, pc-based, CNC, precision, motion.

1. INTRODUCTION

Automated equipment and good shop layout normally improves speed, precision and quality regardless of which type of fabrication is performed. Further, blending mechanical assemblies with computer controls lends flexibility and consistency to fabrication operations. Sometimes the perception of high cost associated with automation in general is not warranted. Various companies have successfully adopted low-cost technologies to improve their profitability. To lower the budgets further, only the degree of automation necessary to do the work while anticipating future upgrades and efficiencies is engaged. In other words, the machine should be adaptable to more automation or future changes when need arises.

Simultaneous movement of several axes using CNC technology yields smooth tool paths that are accurate and repeatable. Although major applications of CNC even today continue to be in conventional machining, it finds applications in non-traditional machining [1] as well as in measurements and inspection [2, 3]. Robots and Rapid Prototyping machines [4, 5] can also be CNC controlled. In fact, any process that can be visualized as a sequence of motions and switching functions can be controlled by CNC.

CNC has also been incorporated in the design of cutting machines that use plasmas and lasers [4, 6, 7] for such operations as engraving and gouging. The cutting of pipes, more so the hazardous high-temperature plasma arc and flame processes, can be improved through such automation as well. Pipes are used for two main purposes: structural support and flow control of liquids, solids and vapours (process piping). The pipes are often cut into various shapes and then welded at junctions. The complexity of the cuts varies with the application. For example, structural piping involves a number of complex profiles where multiple pipe members overlap into a single intersection. The exact angle of intersection coupled with the critical weld preparation angles leave little margin for error. In manual cutting, the accuracy and efficiency depends on the worker's experience. Often additional excessive grinding and filing is required prior to welding.

Process piping include; plumping, HVAC (heating, ventilation and air-conditioning) ductwork, petrochemical plant etc. Though it may involve simpler cuts especially at the end of the pipes, the manual handling of the torch is very cumbersome. Secondly, many cuts of different shapes may be required on the body of each pipe. The geometric calculations may be simpler than in the case of structural piping but more time is required in manual layout, measuring and marking out.

Most of the CNC plasma-arc cutting (PAC) systems in the market consist of torches capable of 5-axis motion to cut flat sheets of metal. Similar to a 5-axis machine for cutting flat sheets, the controllable axes for a 5-axis pipe cutting are; rotation of the workpiece, lengthwise movement of the cutter, rotational movement of the cutter, tilt movement of the cutter and the automatic height sensing. Even though pipe cutting is basically a 3-D job, it does not necessarily require such a complex five-axis machine. This research investigated the capability of a CNC machine in which only the first two axes are simultaneously controlled. Clearly, the motivation to investigate such a simple machine arose from simplification of design and lowering of corresponding cost.

In section 2 of this paper, the theory of PAC process is briefly discussed and some notable advancement since its inception highlighted. The rest of the paper is devoted to the description of the machine developed and the evaluation of accuracy and other quality measures. The shortcomings arising from such simplification of the machine and the PAC process in general; are then pointed out and possible improvements suggested. The compliance of the machine to the

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technique of error modeling and compensation is also briefly discussed.

2. REVIEW OF PAC PROCESS

Plasma arc cutting (PAC) process severs metal by using a constricted arc to melt a localized area of a workpiece, removing the molten material with a highvelocity jet of ionized gas issuing from the constricting orifice. The ionized gas is a plasma, hence the name of the process. Plasma arcs operate typically at temperatures of $10\ 000^0$ -14 000⁰C [8]. Oxygen and air are the most widely used plasma gases but nitrogen and argon-hydrogen mixture are sometimes preferred depending on the material being cut and the quality requirements.

The arc is constricted by passing it through an orifice downstream of the electrode. As plasma gas passes through the arc, it is heated rapidly to a high temperature, expands, and is accelerated as it passes through the constricting orifice toward the workpiece. Further constriction is performed on the open part of the arc by use of a secondary gas, as shown in Figure-1, instead of the nozzle itself. This avoids high rate of wear of the electrode and nozzle due to higher energy density of the plasma through the orifice. The intensity and velocity of the plasma is determined by several variables including the type of gas, its pressure, the flow pattern, the electric current, the size and shape of the orifice, and the distance to the workpiece.



Figure-1. Conventional dual gas PAC.

PAC was invented in the mid 1950's and became commercially successful shortly after its introduction to industry. The ability of the process to sever any electrically conductive material made it especially attractive for cutting nonferrous metals that could not be cut by the oxyfuel cutting (OFC) process. The cutting process has now developed to include cutting of non-metals by non-transferred arc [8].

When compared to mechanical cutting processes, the amount of force required to hold the workpiece in place and move the torch (or vice versa) is much lower with the non-contact plasma arc cutting process. Compared to OFC, the plasma cutting process operates at a much higher energy level, resulting in faster cutting speeds. In addition to its higher speed, PAC has the advantage of instant start-up without requiring much preheat. Instantaneous starting is particularly advantageous for applications involving interrupted cutting, such as severing mesh.

Though increased constriction on the open part of the arc appears an attractive method to increase the energy density, the constriction is often limited by the tendency to develop two arcs in series; one arc between the electrode and nozzle and a second arc between the nozzle and workpiece (Figure-2). This damages the nozzle orifice and also wears the electrode at unacceptable rates.



Figure-2. Double arcing of the plasma.

One method of constriction that has been applied relatively successfully in industries is water-injection, in place of the secondary gas. The radial impingement of the water at the arc provides a higher degree of arc constriction while at the same time reducing double arcing and electrode erosion. Arc temperatures in this region are estimated to approach 50 000 K. However, there are some negative side effects of the high temperature e.g. noise level, toxic gases and ultraviolet radiation.

In a further attempt to improve cut quality and to compete with the superior cut quality of laser systems, High Tolerance Plasma Arc Cutting (HTPAC) systems have been developed. The common feature of the systems is that the plasma jet is forced to swirl as it enters the plasma orifice while a secondary flow of gas is injected downstream of the plasma nozzle as shown in Figure-3.



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Figure-3. HTPAC system.

In HTPAC process, the plasma beam is characterized by high stiffness such that the beam keeps straight and collimated along its axis. This effectively reduces surface modifications and thus lower, or ideally eliminate, the post-processing operation on the cutting edges. Improvements of HTPAC edge quality have already been reported for carbon and stainless steels [9], some aluminum alloys [10] and even pure titanium [11].

One of the earliest forms of mechanized plasma cutting of pipes is the use of portable torch carriages that travel the circumference of the pipe on chains or tracks. Though this appears simple, issues of material handling and time for affixation arise. These strap-on machines are only suitable for short runs and perhaps field service. For effective reduction of cost, it is important to consider the total process; including layout, material handling and cutting. CNC pipe cutting eliminates the need for layout and construction of complicated pipe wraps and patterns.

3. MATERIALS AND METHODS

Figure-4 shows the schematic diagram of the experimental setup. In operation, the pipe is rotated on its roller bed while simultaneously moving the cutting torch back and forth along the pipe's axis thus producing the required shape. The algorithms for cutting various shapes have been developed. A G-code program which is generated in CAD software is loaded into the CNC. The CNC then converts the G-code into commands to direct the motion of the machine axes. The motion type (rapid, linear, and circular), the axes to move, the amount of motion and the motion rate (feed rate) are all programmed, as is the case with most CNC machine tools. The PAC calibration process is also automated such that for every change of material or thickness being cut, a long process of resetting gas mixtures, tweaking pierce heights, pierce delays etc., does not ensure.

The material is easily loaded and unloaded. The pipe is self-centering and fully supported and rotated its full length. The pipe can therefore be cut anywhere along the length of the turning rolls. The machine can easily be equipped with a further axis (CNC or manual) allowing for variable torch bevel angle so that the included weld preparation angle between two members is taken into account. For purposes of programming, Axis 0 (Y-Axis) is the roller axis, Axis 1 (X-Axis) coincides with the torch travel and Axis 3 positions the torch at the right distance away from the material being cut.

The motor controller is interfaced through the ISA bus to a PC and provides a variety of hardware supported motion profiles including trapezoidal profiles, S-curve acceleration and deceleration, parabolic acceleration and deceleration, and constant velocity moves. The motor controller is an LC/DSP-400 4-axis motor controller from Motion Engineering, Inc. Its PID control algorithm delivers quick update rates, stable operation, and easy tuning. To create a motion sequence, the DSP executes a series of frames that are generated by MEI C library functions and sent from the host. The LC/DSP uses a high-performance 40 MHz DSP to execute real-time motion control algorithms, offloading non-real-time functions to the host.

The PAC system consists of the torch with oxygen as the plasma gas and air as the shield gas. Modern plasma torches have self-aligning and self-adjusting consumable parts as long as they are assembled in accordance with the manufacturer's instructions. However, precautions should be taken against double arcing. Double arcing may easily be caused by piercing too close to the workpiece, dragging the nozzle on the workpiece or improper gas flow or current settings. Plasma cutters may use a number of methods to start the pilot arc. Older cutters use a high voltage, high frequency circuit to start the arc. This method has a number of disadvantages, including risk of electrocution, difficulty of repair, sparkgap maintenance, and the large amount of radio frequency emissions. In this work, the contact start method was used. In this method, when the plasma gas begins to flow, the nozzle is blown forward thereby creating a gap with the electrode. This method is particularly suited for plasma cutters working near sensitive electronics, such as CNC hardware or computers.

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Figure-4. Schematic diagram of the setup.

Figure-5 shows some of the common pipe joints that may be cut on the machine. In addition, irregular or uncommon shapes can be plotted, programmed and saved for future use. Figure-6 illustrates an example of actual application of the cut and welded pipes in structural support.



Figure-5. Common pipe joints and cut shapes.



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Figure-6. Application example in structural support.

The PC-based CNC plasma cutting machine is able to integrate the advancements in motion control and software as well as plasma cutting systems that have been around for a few years on high-end CNC plasma cutting machines. There is lots of RAM and virtual memory capability to allow the machine to cut complex metal art shapes. To operate the machine, no extensive knowledge about CNC programming is necessary. All required inputs are made via a user-friendly interface based on windows. Because the PC based CNC plasma cutting machine is so easy to use, it allows less experienced shop floor personnel to produce complex parts very fast.

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4. RESULTS AND DISCUSSIONS

4.1. Experimental results

In sheet metal working, it is common to cut out a shape on the flat sheet before folding into tubular form and welding it. In an analogy to pipe cutting, the contour required for say a round hole through the pipe is not a simple circle; rather, it is the projection of the circle onto the surface of the base tube. Therefore, the developed pattern is first laid out as if the pipe is unrolled flat. The cut is then split into a sequence of straight lines or circular arcs that make up the desired pattern in the X-Y plane. Finally, the cutting head is positioned on the Y position of the rotary axis, and the cutting is done by converting the Y coordinates into the rotary angle i.e.;

$$y = R \cdot \theta \tag{1}$$

where R is the radius of the pipe being cut.

In other words, the axis of rotation of the numerically control machine has been treated, from a control standpoint, as a linear Cartesian axis. In this manner, the entry of data into the machine control system is greatly simplified. Table-1 shows the specifications of three shapes cut on a pipe of diameter 115 mm and wall thickness of 4 mm.

Table-1. Specifications of cut shapes.

Shape	Diameter	Slope
	(mm)	(degrees)
Circle (saddle)	60	45
Circle-T (A)	60	45
Circle-T (B)	76	45

Figures 7, 8 and 9 show the error graphs for circle (saddle), circle-T (A) and circle-T (B) cutting, respectively. The error is the difference between the command and the actual position of the cutter. The actual position is determined from the signals generated by encoders attached to the servo motors while the command is derived from the AutoCAD drawing. In each case, the origin of the X-Y coordinates was made to coincide with the point where the cutting commences.



Figure-7. Error graph of circle (saddle) cutting.







Figure-9. Error graph of circle-T (B) cutting.

4.2. Accuracy and cut quality assessment

The graphs show that high accuracy is achieved throughout and is within the acceptable range for shopfloor plasma-cut parts [12]. In fact the accuracy rivals that of acceptable laser cuts [13] though this may be expected to deteriorate with the aging of the machine. The



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plasma cutter removes material while cutting and the width of the cut (kerf) might produce an undersized part. However, an offset could easily be used to alleviate the problem. Specified offsets can be easily created in most CAD packages. For example, the Y-values of the circle-T (A) cutting (Fig. 8) show almost constant positive error. This is a good candidate for the application of an appropriate offset to eliminate or minimize the error. Further improvements in the cutting software offer better control of torch lead-in and kerf allowance. This better control of the cut path minimizes the number of material pierces, which in turn leads to longer consumable life and greater cut part accuracy.

Other factors to consider in evaluating the cut quality include surface smoothness, kerf angle, dross adherence and metallurgical defects in the heat affected zone (HAZ). These factors are affected by the type of material being cut, the equipment being used, and the cutting conditions. Drag lines are the major contribution to surface roughness in plasma cutting. As the plasma arc cuts through the metal, the electrical contact jumps down the face of the cut. At faster speeds, the anode attachments move backward as they move downward through the metal, leaving behind drag lines that angle backward. At slower speeds, the current jumps straight down through the metal, leaving nearly perpendicular drag lines. Smoothness of the power supply and torch design is the key factors to the control of the severity of drag lines.

Further, either too high or too low a cutting speed can cause dross, but there is usually a window in between that will result in minimum or no dross. Dross is the material that melts during cutting and adheres to the bottom edge of the cut face. Low-speed dross forms because when the cutting speed is too slow, the kerf gets wider and it gets harder for the pressurized jet to blow away the molten metal. High-speed dross, on the other hand, forms when a higher cutting speed is used without increased current thereby making the arc unstable.

Normally the plasma jet tends to remove more metal from the upper part of the kerf than from the lower part. This results in beveled cuts wider at the top than at the bottom. The bevel (4 to 5 degree) is not pronounced for thin material. Because the bevel occurs on one side of the cut when orifice gas swirl is used (HTPAC system), the cut can be arranged so that the bevel is on the piece to be discarded or at least on the less critical part.

During PAC, the material at the cut surface is heated to its melting temperature. This produces a heataffected zone along the cut surface, as with fusion welding operations. The heat not only alters the structure of the metal in this zone but also introduces internal stresses from the rapid expansion, upsetting, and contraction of the metal at the cut surface. The depth to which the arc heat will penetrate the workpiece is inversely proportional to cutting speed. Because of the high cutting speed of PAC process, the HAZ is limited to a very narrow range. Watershielded and water-injection PAC may be employed to reduce the HAZ further due to the quenching effect of water. Waterjet and laser cutting are more precise than plasma. Nevertheless, HTPAC technology is dramatically improving the cut accuracy possible with plasma technology. Plasma technology, particularly at low amperages, has cost and housekeeping advantages. Further refinements in controls and extension of consumable life will make plasma an even more productive and precise cutting technology than it is today. As systems improve cut quality even further, plasma is progressively replacing the more expensive cutting lasers.

4.3. Compliance of machine to error modeling and compensation technique

CNC machine tool manufacturers and users are shifting from very accurate designs to the technique of error compensation as a means of achieving high precision. The basic philosophy behind this concept is to monitor or measure the amount of inaccuracy which could arise and compensate the same during actual processing. Therefore, the technique enables one to produce high precision components even when using a relatively less accurate machine tool.

The major types of error in CNC machine tools are geometric/kinematic, thermal and cutting-force induced errors. The error caused by cutting forces depends on the type of tool, the workpiece and the cutting conditions adopted. For a PAC system, the cutting force errors are insignificant. Though plasma cutting may involve the creation of a heat-affected zone (HAZ), quasistatic thermal errors are very small. Therefore geometric and kinematic errors would make up the major part of the inaccuracy of a PAC machine.

Kinematic errors are concerned with the relative motion errors of several moving machine components that need to move in accordance with precise functional requirements. These errors are particularly significant during the combined motion of different axes as in the case of gear hobbing or profile machining where coordination of rotary with respect to linear axes or linear with respect to linear axes is of prime importance. On the other hand, geometric errors exist in a machine on account of its basic design, the inaccuracies built-in during assembly and as a result of the components used on the machine. Geometric errors are mostly repeatable and therefore their compensatory actions would be very effective [14].

The volumetric errors in whole working zone are difficult to measure directly due to the involvement of rotational errors. Therefore, kinematic models are used to synthesize the volumetric error by the use of measured error components. There is a great amount in the literature about such machine tool error modeling and compensation but the measurement of the error components using a convectional laser interferometer often take too long, running into days of machine downtime [15]. There has been some developments towards reducing the number of measurements by taking diagonal-based measurements and calculating some or all the error components theoretically [15, 16], but some researches [17, 18] have

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criticized the methods as having limitations that can lead to large unpredictable errors. The limitations arise from the assumptions made in modeling the complex machine tools. Clearly, reducing the number of axes (where possible) is the most effective way in rendering a machine tool more compliant to the technique of error modeling and compensation.

5. CONCLUSIONS

For many people, the world of plasma cutting has been a complex and daunting place, with a cryptic set of rules that can be mastered only by highly trained technicians after weeks of training. However CNC automation introduces higher precision, repeatability and speed into plasma cutting operations. The developed CNC pipe profile cutting machine has the capability of producing high precision parts by simultaneous control of only two axes. Though the motivation to study the 2-D machine arose from the simplification of design and lowering of cost, improvement in error modeling and compensation can also be envisaged.

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