Involute Spline Profile Generation Using Wire EDM Process

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Abstract— Today's Mechanical Engineering field is growing rapidly in designing techniques to manufacture Splines and Gears. Over the decades, numerous methods and manufacturing processes have been used in making the various kinds of Splines based on various criteria, including applications, reliability, life time, processing time and manufacturing cost. This work is also carried out with the same notion of reviewing of manufacturing an External Involute Spline cutting tool using Wire Electrical Discharge Machining process and Vertical Milling Machine. Wire electrical discharge machining (WEDM) is an extremely accurate type of manufacturing process. This technique was commercially developed in the 1970s. Spline is a long flexible strip of metal/plastic/wood used to produce the curve through the known set of data points. The curved shape of strip is obtained by pulling it into the transverse direction using the lead weights or pegs.

Key words: Wire EDM, Involute spline, Involute profile

I. INTRODUCTION

A. Principle of Wire Edm

The principle of wire electrical discharge machine is Spark Theory. In wire EDM, the conductive materials are machined with a series of electrical discharges (sparks) that are produced between an accurately positioned moving wire (the electrode) and the work piece. High frequency pulses of alternating or direct current is discharged from the wire to the work piece with a very small spark gap through an insulated dielectric fluid (water) [1]. Huge number of sparks can be observed at one time. This is because actual discharges occurs more than one hundred times per second, with discharge sparks lasting in the range of 1/1,000,000 of a second or less than that. The amount of the metal removed during this small period of spark discharge depends on the desired cutting speed and the surface finish required. Fig. 1 shows the schematic diagram of WEDM machine setup.

B. Working of Wire Edm

In the wire electrode discharge machining, a thin single-stranded metal wire is fed through the work piece.

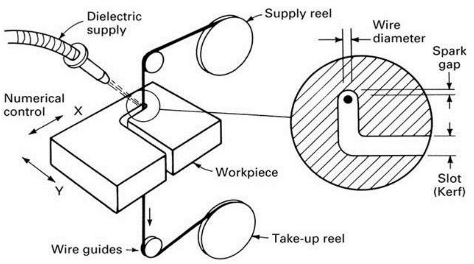


Fig. 1 Schematic Diagram of Wire EDM process

This process is similar to contour cutting with a band saw, a slowly moving wire travels along a prescribed path, cutting the work piece. This process is used to cut plates as thick as 300mm and to make punches, tools, and dies from the hard metals that are too difficult to machine with other methods. It also creates intricate components for the electronic industries. The wire, which is constantly fed from the spool, is held between upper and lower diamond guides. Guides move in the x-y plane, usually being CNC controlled and on almost all modern machines like HS 70a the upper guide can also move independently in the z-u-v axis, giving rise to the ability to cut tapered and transitioning shapes and can control axis movements in x-y-u-v-i-j-k-l-. This gives the wire-cut EDM the ability to be programmed to cut very intricate and delicate shapes [20]. The wire is controlled by upper and lower diamond guides that are usually accurate to 0.004mm, and can have a cutting path or kerf as small as 0.12mm using ø0.1mm wire, though the average cutting kerf that achieves the best economic cost and machining time is 0.335mm using ø0.25mm brass wire. The wire is usually made of brass, copper, tungsten, or molybdenum and multi-coated wire. The wire diameter is typically about 0.3mm for roughing cuts and 0.2mm for finishing cuts. The wire should have high electrical conductivity and tensile strength, as the tension on it is typically 60% of its tensile strength. The wire usually is used only once, as it is relatively inexpensive compared to the type of operation it performs. It travels at a constant velocity in the range of 0.15 to 9m/min, and a constant gap (kerf) is maintained during the cut. The trend in the use of dielectric fluids is towards clear, low viscosity fluids. The reason that the cutting width is greater than the width of the wire is because sparking also occurs from the sides of the wire to the work piece, causing erosion. This "overcut" is necessary, predictable, and easily compensated for. Spools of wire are typically very long. For example, an 8kg spool of 0.25mm wire is just over 19 kilometers long. Today, the smallest wire diameter is 20 micrometers and the geometry precision is not far from +/- 1 micrometer. The wire- cut process uses water as its dielectric with the water's resistivity and other electrical properties carefully controlled by filters and de-ionizer units. The water also serves the very critical purpose of flushing the cut debris away from the cutting zone. Flushing is an important determining factor in the maximum feed rate available in a given material thickness, and poor flushing situations necessitate the reduction of the feed rate. Along with tighter tolerances multi-axis EDM wire-cutting machining center have many added features such as multi-heads for cutting two parts at the same time, controls for preventing wire breakage, automatic self-threading features in case of wire breakage, programmable machining strategies to optimize the operation.

C. Performance Parameters

1) Cutting Speed:

For Wire EDM, cutting speed is an important characteristic and it should be as high as possible to give least machining cycle time. The current cutting speed is digitally displayed on the machine display screen. The machining time "s" is recorded by the Wire EDM machine time indicator. The cutting speed is measured after the machining the specimen distance of and recorded. [2]

2) Spark Gap:

Spark gap or overcut is one of the responses which is very effective in this work. The spark gap is measured in order to study the correlation between machining parameters and the spark gap. Spark gap is shown in Fig. 2. The unit used is mm. Spark gap can be calculated by the following formula. [2]

$$spark\ gap = \frac{kerf\ width - wire\ diameter}{2} \quad ..(1)$$

$$kerf\ width = \frac{hole\ dimension - block\ dimension}{2} \quad ..(2)$$

3) Material Removal Rate:

The material removal rate of the work piece is the volume of the material removed per minute. The following are equations used to determine material removal rate (MRR) value.

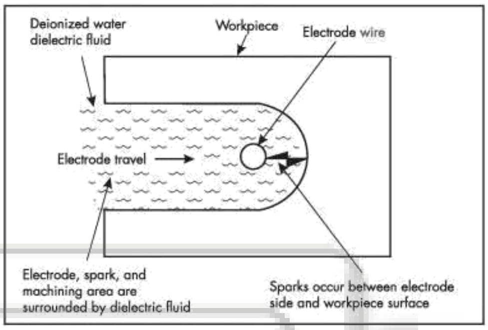


Fig. 2 Wire EDM cut with spark gap

$$volume = spark\ gap\ X\ machine\ distance\ X\ work\ piece\ thickness \quad \ldots (3)$$

From the material properties, the density of the machine insert (Solid Carbide) can be known. The mass of material that was removed by Wire EDM process can be known by,

$$mass = density\ X\ volume \quad \ldots (4)$$

Therefore, Material Removal Rate (MRR) is measured by,

$$MRR = \frac{Mass}{Machinig\ Time} \quad \ldots (5)$$

II. INVOLUTE SPLINE

Spline is a long flexible strip of metal/plastic/wood used to produce the curve through the known set of data points. The curved shape of strip is obtained by pulling it into the transverse direction using the lead weights or pegs. The lead weights or pegs hold the strip in the curved position. The Spline shape of the strip can be obtained by varying the number of the lead weights and its positions on the board by the drafters. The resulting curve appears smooth and fits the data points. The term *Spline curve* was originally referred to a curve drawn in this manner by a drafter. This Spline curve is a natural cubic Spline possessing C^2 continuity. [3]

In modern computer graphics, Splines are preferred for the following applications:

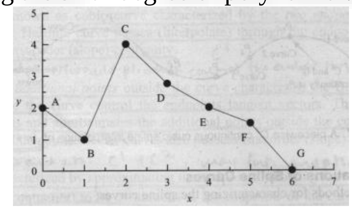
- Design of various types of curves
- Design of surface shapes
- Digitization of drawings for the computer storage
- Specification of the animation paths for the camera or eyes
- Design of aerodynamic efficient automobile bodies
- Design of aerospace structures such as surface of airplanes, rockets etc.
- Design of hydrospace structures such as surface of ship hulls, submarines etc.
- Design of curved shape products such as shoes, bottles etc
- Designing of curved involute profile of external and internal gears.

Now, the question arises, how to generate a Spline curve on computer? This curve can be mathematically described with a piecewise cubic polynomial function, which satisfies C^1 (slope) and C^2 (slope derivative) continuities at the boundaries of the curve segments. Thus, in computer graphics, the Spline curve is a composite curve formed by joining the polynomials piecewise, satisfying the specified continuity conditions at the boundary of curved segments. Splines classification depends on particular type of polynomials used for drawing the curve with certain specified boundary conditions. For example, let us analyze the interpolation of data points shown in Table 1. [3]

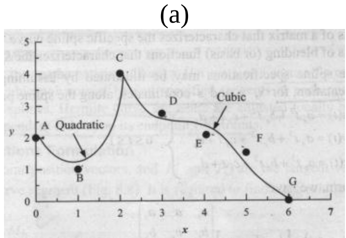
X	0	1	2	3	4	5	6
Y	2	1	4	2.75	2	1.5	0

Table 1 Data points for the interpolation [3]

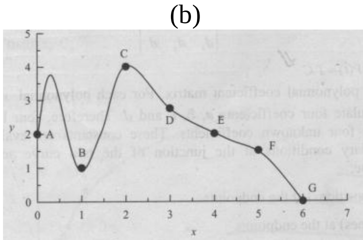
Fig.3 shows the piecewise interpolation of seven data points using the polynomials of various degrees. For example, Fig. 1.1a shows the piecewise linear interpolation of data points. Linear interpolation does not generate smooth curve. Fig. 8.6b shows the quadratic interpolation of data points for x < 2; however, for x > 2, curve becomes smooth because of the fourth degree of polynomial (5 data points). At x = 2, the curve has corner and derivative of curve is discontinuous. Only C^0 (position) continuity exist at x = 2. In fig. 1.1c, the interpolation of seven data points is obtained by considering the sixth degree of polynomial. [3]



(a)



(b)



(c)

Fig. 3 Piecewise Interpolation of Data Points
(a) Linear Interpolation (b) Quadratic Interpolation (c) Polynomial Interpolation [3]

Suppose we have to find out a Spline curve to fit (n+1) control points. The curve fitting for the (n+1) control points require n curve segments as shown in fig.4. A parametric cubic Spline given by equation 1.1 has four coefficients. Thus a total of 4n coefficients are required for the n curve segments. The main problem with the natural or drafting Spline is the local control. If any one of the control point shifts, the entire curve is affected; therefore, does not allow the local control for the natural Spline curves. The designer does not prefer the natural cubic Spline because it is not possible to restructure part of the curve without affecting the entire curve.

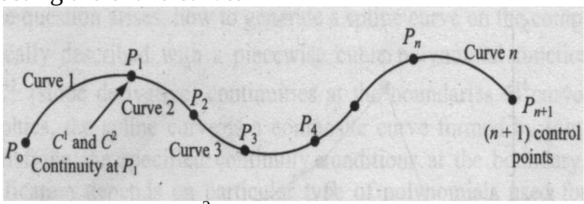


Fig. 4: A piecewise C^2 continuous cubic Spline interpolation of (n+1) control points [3]

Third order cubic polynomial

$$x(t) = at^3 + bt^2 + ct + d \qquad \text{... (6)}$$

A. Specification of Spline Curves

There are three methods

- On the basis of set of imposed boundary conditions.
- On the basis of matrix that characterizes the specific spline curve.
- On the basis of blending (or basis) functions that characterizes the spline curve.

These three spline specifications may be illustrated by assuming the cubic polynomial parametric representation, for x, y and z, along the spline path in parameter t as [3]

$$\left.\begin{aligned} x(t) &= a_x.t^3 + b_x.t^2 + c_x.t + d_x \\ y(t) &= a_y.t^3 + b_y.t^2 + c_y.t + d_y \\ z(t) &= a_z.t^3 + b_z.t^2 + c_z.t + d_z \end{aligned}\right\} 0 \le t \le 1 \qquad \text{... (7)}$$

In matrix form, we have

$$\{x(t) \quad y(t) \quad z(t)\} = \{t^3 \quad t^2 \quad t \quad 1\} \begin{pmatrix} a_x & a_y & a_z \\ b_x & b_y & b_z \\ c_x & c_y & c_z \\ d_x & d_y & d_z \end{pmatrix} \qquad \text{... (8)}$$

Or $$P(t) = T.C \qquad \text{... (9)}$$

Where '*C*' is the polynomial coefficient matrix. For each polynomial *x(t), y(t)* and *z(t)*, it is required to calculate four coefficients *a, b, c* and *d*. Therefore, four boundary conditions are required for the four unknown coefficients. These constants are evaluated by imposing the sufficient boundary conditions at the junction of two curve segments. The boundary conditions may be: [3]

- Constraints (positions) at the end points.
- Tangents (slopes) at the end points.
- Continuity at the junction between the curve segments.

B. Classification of Spline Curves

Based upon the techniques for the evaluation of four coefficients *a, b, c* and *d*, there are three major classifications of spline curve:

- HERMITE CURVE: Hermite curve is also known as cubic curve characterized by the two endpoints and tangent vectors at the endpoints. Hermite curve passes (interpolate) through the endpoints of the curve segment and possesses first order (slope) continuity. [3]
- BEZIER CURVE: Two endpoints and two additional points outside the curve characterize the Bezier curve. The additional points outside the curve control the endpoints tangent vectors. Thus, Bezier curve interpolates the endpoints and approximates the additional points outside the curve, i.e., they do not pass through the outside points. Bezier curves also posses first order (slope) continuity. [3]
- B-SPLINE CURVE: B-Spline curves are characterized by approximating the endpoints, allowing first and second order derivatives (C^1 and C^2 continuity) to be continuous at the endpoints of the curve, under certain conditions, the curve may interpolate the endpoints. [3]

III. EXPERIMENTAL WORK

A. Test Material Specification & Equipment:

By looking at the mechanical and physical properties of the different materials we chose Aluminum specimen as a test specimen for testing the Solid Carbide Machine insert with Involute profile [4].Physical Properties of Aluminum specimen are tabulated below in Table 2:

Properties	Value
Density (g/cc)	2.7
Melting Point (°C)	582-652
Modulus of Elasticity Tension(GPa)	68.9
Modulus of Elasticity Torsion(GPa)	26

Table 2 Physical properties of Aluminum specimen

Parameters	Value
Brinell's Hardness	95
Ultimate Tensile Strength (MPa)	310
Tensile Yield Strength (MPa)	276
Modulus of Elasticity (GPa)	68.9
Poisson's Ratio	0.33
Fatigue Strength (MPa)	96.5
Machinability	50%
Shear Modulus (GPa)	26
Shear Strength (MPa)	207

Table 3 Mechanical Properties of Aluminum:

The experimental setup of wire EDM machine is shown in the following fig.. Table 4 has the specifications of the shown Wire EDM machine.

The NC code is copied into the machine through the external storage drive. Before setting up the work piece onto the machine first we need to know the global co-ordinate system (GCS) of the machine and the co-ordinate system of the work piece. Then the work piece holder is fixed to the wire EDM machine rigidly with proper supports as shown in Fig. 5.

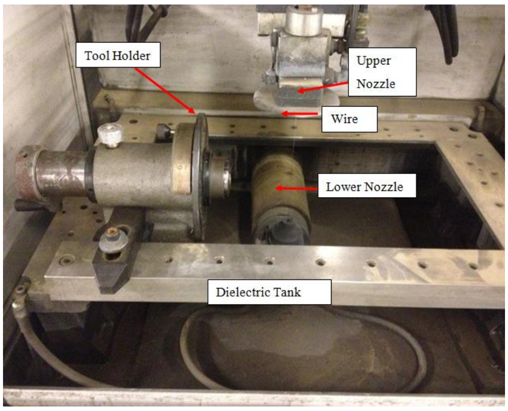


Fig. 5 Experimental Setup of the Wire EDM Machine

Maximum Work Piece Height	170mm
Maximum work piece Weight	100kg
Maximum Table Feed Rate	600mm/min(Positioning) 300mm/min (Machining)
Wire Diameter	0.1mm, 0.15mm, 0.2mm, 0.25mm, 0.3mm
Wire Feed Rate	40 ~250mm/sec
Wire Tension	3~25N
Water Supply Unit Capacity	360L
Least Input Increment	0.0001mm (X, Y, Z, U, V axes), 0.000010 (B-axis)
Least Command Input	0.001mm
Input Power Supply	440 10% (50/60Hz 1Hz)
Total Input	13.5KVA
Open Voltage	40V, 50V, 60V, 70V, 85V
Machining Current	30A

Table 4 Wire EDM Machine Specifications

IV. ADVANTAGES AND LIMITATION

A. Advantages of Wire Edm

The process of wire electrical discharge machining (known as WEDM or wire EDM) offers many advantages which are unattainable using other methods. Over the last fifteen years, wire EDM technology has developed into a standard and popular machining technology. In many operations formerly performed by conventional manufacturing processes, the process of wire EDM is regularly less expensive, infinitely more accurate, and considerably time saving. Following are some major advantages of wire electro discharge machining process:

– Exotic Metals Capabilities
– Complex Geometries
– Stacking Plates
– Racking of Parts
– Raw Materials
– Hardness
– Burr Free
– Flexibility
– EDM delivery

B. Limitations of Wire Edm

Following are some major advantages of wire electro discharge machining process:

– Slow Material Removal Rate (MRR).
– Reproducing sharp corners on the work piece is difficult due to electrode wear.
– Limited for ferrous alloys but no reaction works in non-ferrous such as plastic, fiber, wood and so forth.
– Wire EDM machine can only be operated with the present of electricity.
– Unable to interpret technical or manual data/drawing. Wire EDM machine is enable to interpret and receiving drawing from such as CATIA, AutoCAD, Unigraphics, Solid Edge, Solid Works and etc.
– The control system of the electrode may fail to react quickly enough to prevent the tool and work piece to get in contact with a consequent short circuit. It is unwanted because a short circuit contributes to the removal differently from the ideal case. The flushing action can be inadequate to restore the insulating properties of the dielectric so that the flow of current always happens in the point of the inter-electrode volume (this is referred to as arcing), with a consequent unwanted change of shape (damage) of the tool-electrode and work piece.

V. APPLICATIONS OF WIRE EDM

Wire EDM has a wide range of applications which are growing by time day by day. It is extensively used in automotive, aerospace, molds, tool and die making industries. Wire EDM also has applicability in the medical, optical, dental, jewelry industries. The machine's ability to operate unattended for hours or even days further increases the attractiveness of the process. Accuracy of high value with intrinsic design and on exotic material has increased its applicability in medical and R&D areas. Conventional EDM technique process requires many hours of electrode fabrication as well as many hours of manual grinding and polishing. With Wire EDM the overall fabrication time is reduced by around 37% and the processing time is reduced by 66%.

Following are the few major applications of wire EDM process:

– Parts with complex geometry
– Parts requiring tolerances in the range of tenths
– Parts where burrs cannot be tolerated
– Delicate parts that are susceptible to tool pressure
– Progressive, blanking and trim dies
– Extrusion dies
– Precious metals
– Narrow slots and keyways
– Mold components
– Tooling for forging or injection molding operations
– Medical and dental instrumentation
– Cutting hardened materials such as carbide
– Cutting difficult to machine materials like hastily, Inconel and titanium

- Aerospace, defense and electronic parts
- Prototypes of different parts
- Production parts

VI. RESULTS & CONCLUSION

The Solid carbide Machine inserts are successfully cut in the Wire EDM machine to get the involute Spline profile. Total of three inserts were cut on two specimens in Wire EDM in the process of manufacturing and testing.

Fig. 6: Involute profile cut on Specimen1 (left) and Specimen2 (right)

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