Novel Tool Design Method for Orbiting EDM -A 2nd Approach on Design Automation Developed in CAD-*

Tutik SRIANI** and Hideki AOYAMA**

**School of Integrated Design Engineering, Keio University

3-14-1 Hiyoshi, Kohoku-ku, Yokohama, Japan

E-mail:tutik@ina.sd.keio.ac.jp

Abstract

Tool design for orbiting EDM process often encounters some difficulties to adjust for EDM orbit and machining overcut concurrently. In orbiting process, the tool sweeps out some extra volume due to the additional orbit motion. Hence, it is compulsory to adjust tool geometry based on the chosen orbit cycle to avoid dimension distortion on the final product. Currently, tool correction is done manually since there is no CAD package which provides a specific assistance to adjust the tool geometry for orbital motion. Therefore, design process becomes lengthy and more prone to error due to manual correction process. The authors have proposed a tool design principle for orbiting purposes. Presented in the paper is continuation of the previous work, which emphasizes an automation strategy of tool design developed inside CAD system. The tool is compensated automatically for overcut and EDM orbit, and checked for its validity. The developed CAD system has been tested for a few EDM applications with complex shapes and proven effective to cut tool design time and human-related failures which are commonly found during manual design processes. Experimental validation for a complex part was executed with a promising result.

Key words: EDM, Orbiting, Tool Design, Automation, Non-Uniform Offset

1. Introduction

1.1 Static EDM and Orbiting EDM

Electrical Discharge Machining (EDM) technology provides the ability to process difficult-to-machine materials with accurate machining result. EDM consists of tool and workpiece, which are charged in different polarity and immersed in a dielectric medium. As high current flows in, electrical discharge emerges and removes some portion of both parts until the final shape is achieved. This technique allows treating tool steel to its full hardness prior EDM, hence avoid the problems of geometry distortion caused by material post treatment ⁽¹⁾. Recently, EDM becomes a common manufacturing method to fabricate parts especially in aerospace and automobile where production quantities are relatively low ⁽²⁾, mould and die industries, and small and burr-free hole drilling ⁽³⁾. This process also provides an efficient way to produce delicate parts which might not be feasible by traditional machining.

In static EDM, the tool only moves in Z direction, causing high tool wear particularly for deep cavity machining since the electrical discharges are concentrated only on the tip of the tool. High tool wear leads to the requirements of four to six tools to achieve an accurate product dimension during machining process ⁽⁴⁾. All tools must be undersized in an

*Received 13 Oct., 2010 (No. 10-0467)

[DOI: 10.1299/jamdsm.4.1261]

Copyright © 2010 by JSME

individual basis to allow different spark gap caused by specific combination of machining parameters used for each machining. Orbiting adds extra tool movement during machining process as depicted in Fig. 1. This movement improves fluid circulation and effectively removes accumulated debris inside EDM working zone, which leads to a minimum tool wear process. Fig. 2 illustrates comparison of debris distribution on EDM working zone in static and orbiting EDM. The orbiting provides a tool sideways, in which engaging wider surface area due to the applied motion. Thus, debris can be removed from the working zone easily and tool wear becomes very little and more uniform. Orbiting technique allows the use of higher energy without sacrificing surface quality since the additional power is spread out all over the surface, therefore reduces machining time. Reduction in tool wear causing fewer tools is required to produce final shape. Further savings are realized from less direct labor and time required to make or redress multiple tools. In short, this technique has been proved to reduce tool wear, shorten machining time, and also improves surface finish and dimension accuracy ⁽⁵⁾⁽⁶⁾.

Regardless of all benefits that orbiting offers, tool designers often struggle to design accurate tool geometry for orbiting EDM purposes. The difficulty appears because the designer needs to undersize the tool with two different compensation rules. The first compensation applied for spark gap or machining overcut, just like under-sizing the tool used for static EDM, and the second compensation applied to permit for EDM orbit allowance (orbit gap). Combining these compensations is a difficult task since spark gap applies only for magnitude while EDM orbit appears as a vector function. Orbiting is a continuously controlled tool motion in XYZ axis that is created from series of directed line segments which has path as well as magnitude. An efficiency loss can be observed due to application of orbit motion depending on the tool geometry ⁽⁷⁾.

Fig. 1 Tool movement in orbiting EDM

Fig. 2 Comparison of debris distribution in EDM working zone

The authors have proposed a new method to correct tool geometry for the chosen orbit path ⁽⁸⁾, however, the calculation of corrected tool surface is still done manually. Currently, CAD software equipped with tool correction package for spark gap as well as EDM orbit is not yet available on the market. Tool designers usually perform manual correction for both spark gap and orbit gap. This process requires high knowledge of tool design and likewise the nature of EDM orbit. The biggest challenge that the designers have to deal with is combining the compensation of spark gap and EDM orbit simultaneously. Combination of these two factors might be easy for tool with simple geometry but not for complicated ones. Furthermore, manual design consumes a huge amount of design time and prone to human-failure ⁽⁹⁾.

1.2 Related Works

Many dies and moulds require multiple cavities and each needs a specific tool geometry which machining runs in a sequence until all cavities are accomplished, hence moulds production demands a lot of manufacturing time ⁽¹⁾. Very few works has also been observed to facilitate the ease of tool design process. EDM works mainly concentrate on the optimization of material removal rate, tool wear rate and surface finish ⁽¹⁰⁾. For example, an attempt to make helical thread cavities in AISI H13 tool steel dies with Cu-W tool using orbiting EDM (round orbit) for semi-finish and finish regime was performed successfully ⁽¹¹⁾. This work reports an appropriate combination of machining parameters and type of material to give precise and sharp details. A study about cost estimation using design features and tooling parameters based on cost drivers and cost modifiers was done ⁽¹²⁾, but the design geometry of the tool itself was not considered. A tool design and manufacturing work for micro milling tools are done using finite element method analysis ⁽¹³⁾ by optimizing geometry of micro tool based on the obtained stress distribution, which only covers for static EDM operation. A review about manufacturing EDM tool using rapid tooling (RT) reported that this technique allows building prototype tools for complex parts directly from CAD model and compress manufacturing time ⁽¹⁴⁾. Yet, this work only applies for static EDM and the tool performance generated by RT does not meet the desirable standards for practical use. An investigation about the effect of different tool geometry and size factor was reported in the field of static EDM ⁽¹⁵⁾. They found that circular tool shape gives higher MRR and lower TWR compared to triangular and square tools, while another work found that square electrode is preferable to make precise dimension ⁽¹⁶⁾ since it possesses less wear.

The authors proposed a concurrent compensation of spark gap and EDM orbit with non-uniform offset of two-dimensional orbit motion ⁽⁸⁾, and this paper proposes automation of tool design for orbiting EDM purposes for the continuation of the previous report. This method automates a direct compensation of spark gap and EDM orbit concurrently inside CAD system. The tool design principle is based on non-uniform offset which will be explained in detail in the next section. Design automation avoids design failure due to miscalculation of manual tool offset particularly for complex parts, and also cut tool design lead time as there is a need to develop tool design and manufacture system with minimum user interventions to reduce lead time and manufacturing costs ⁽¹⁾. The developed system also gives direct output in the form of CAD data to the user, thus the output is very convenient to carry on the subsequent tool manufacturing process.

2. Methodology

2.1 Current Design Principle

An EDM cavity is always larger than the tool used to generate it. The difference between the size of the tool to the size of cavity is called machining overcut, which value constant throughout the working surface of the tool as depicted in Fig. 2. The overcut value

varies depending on the selection of machining parameters, and can be classified into three clusters of rough overcut, semi-finish overcut, and finish overcut. When designing tools for static EDM, the shape of the tools is taken as the core of the cavity and subsequently extracted by machining overcut. This extraction applies uniformly to EDM working zone which allows tools to generate precise cavity geometry.

Introduction of orbit motion adds some tool cut-swept-volume to the workpiece being machined. The quantity of the swept volume depends on the type of orbit path used in the process and also the orbit length, or orbit gap, which value is determined by the user. In the tool design process, besides extracting tools for overcut allowance, the tools also need to be extracted for orbiting allowance, which value depends on orbit gap and type of orbit. A CAD package of tool design for orbiting EDM is currently not available on the market, and designers usually perform manual tool extraction for this purpose. In manual design, designers usually apply uniform offset to the tools. This offset is a summation of overcut and orbit gap which applied uniformly to the surfaces of EDM working zone. As a matter of fact, uniform offset is solely valid for very limited cavity geometries like circular shape or cuboids. This principle is not valid when the cavity has complex shape and further creates geometry difference between design and product. Fig. 3 illustrates the application of uniform offset for three different geometries; circular, square, and a square with variation of fillet radius at its three corners plus a chamfer on the other corner. The uniform offset (t) is defined as the summation of spark gap and orbit gap. The tools shaped by uniform offset are used for orbiting EDM with each assigned path. Fig. 3 reveals that the third geometry failed to meet design requirement due to different fillet radius and chamfer produced on the respective corners, also occupying larger area. Thus, it comes to conclusion that uniform tool offset application is limited by geometry and proven failed for part contains complex geometries.

Fig. 3 Result of uniform offset application

Fig. 4 Non-uniform offset implementation for complex geometry

2.2 Proposed Design Method

As mentioned earlier, uniform offset cannot be applied casually to design tool for orbiting EDM since uniform offset is valid only for limited geometries. Therefore, other technique to compensate for orbital motion as well as EDM overcut is absolutely required to avoid design failure.

A non-uniform offset principle is proposed to be used for tool design of orbiting EDM. This method consists of two steps of tool extraction. First tool extraction applies to compensate for orbital motion, which values vary with refer to the orbit type and the length of orbit gap. Second tool extraction applies to correct for EDM overcut, which is constant throughout the surface of EDM working zone. Fig. 4 describes the principle of non-uniform offset utilized in this work to compensate for the last shape presented in Fig. 3 using a square orbit. In this model, the first compensation for 1 mm orbit gap is applied non-uniformly for square orbit to the EDM working zone. It can be seen from Fig. 4 that the tool extraction varies from 1 mm to maximum of 1.414 mm, which is the hypotenuse value of the orbit gap. From this geometry, the second compensation of machining overcut is applied. A uniform offset of spark gap, in this case is 0.5 mm, is applied uniformly throughout the tool surface. The result from the second tool extraction becomes the physical model of the tool shape that has been compensated for both orbital motion as well as EDM overcut.

Fig. 5 Compensation of two-dimensional orbit cycles to an ellipse shape

Fig. 6 Steps of tool design to compensate for EDM orbit and overcut

2.3 Typical Orbit Motion

The non-uniform offset application of the model depicted in Fig. 4 is executed with respect to the type of orbit path. Orbit path is classified as a vector function which has direction properties as well as magnitude. The orbit magnitude, or orbit gap, is defined by the operator prior machining. In this extraction method, compensation for orbital motion depends on the type of orbit path and also geometry of the feature being processed. Fig. 5 gives compensation sample for various orbiting patterns of an ellipse shape tool. The orbit gap applied was 1 mm for each orbit cycle. It can be seen from this figure that each orbit path gives a unique tool subtraction which refer to the orbit vector itself. Therefore, it is logical to use non-uniform offset which based on type of orbital motion since the tool is adjusted to the applied motion instead of applying tool offset based on orbit magnitude. The detail of how the offset is executed in this method will be explained in the next section.

3. Design Automation

3.1 Tool Design Principle

Tool design principle applied in this method utilizes reverse process of EDM to get a correct tool shape for orbiting application. This method is implemented in SolidWorks as a package to facilitate easier tool design process. The physical tool is achieved in the following step:

Step 1 Create the model in CAD with all desired dimension. Take a negative Boolean core from this model as an *EarlyTool* shape.

Step 2 Decide which orbit cycle to be used for this model and the length of orbit gap. Calculate all coordinates of the orbit vertices based on the chosen orbit cycle and the orbit gap length.

Step 3 Copy the *EarlyTool* shape and translate each copy to each coordinate of orbit vertices. The number of copy and translation process follows the number of orbit vertices.

Step 4 Perform a Boolean intersection over all solid bodies that have been created from previous step. At this point, the Boolean body becomes the tool that has been adjusted for the chosen orbit cycle.

Step 5 Select EDM working faces from the combined body, and apply a uniform offset of spark gap to these faces. This is the last step of tool design for orbiting EDM, which generates a *PhysicalTool* shape that has been compensated for both orbit cycle as well as EDM overcut.

The tool design steps explained in this section is illustrated in Fig. 6. The chosen orbit cycle for this model is square orbit. It can be observed from this figure that in contrast with static EDM process, two-dimensional orbiting affects the final tool geometry only at the orbiting plane whilst tool extraction remains constant in the direction of burn (Z axis).

3.2 Tool Validation

Precision is very sensitive case in terms of design quality. In order to confirm that the compensated tool created earlier is capable of producing geometry that agrees design requirement, the tool has to pass for a validation check prior manufacturing process. To validate the compensated tool, a simulation of orbiting EDM process is executed in SolidWorks. Continuing the tool design steps that have been formulated in section 3.1, tool validation follows:

Step 6 Copy the *PhysicalTool* shape and translate each copy to each coordinate of orbit vertices.

Step 7 Perform a Boolean addition to the solid bodies created earlier. At this point, the Boolean body becomes the tool shape that has been added by orbit swept volume.

Step 8 Select EDM working faces from the Boolean body, and add a uniform layer of spark gap to fatten the Boolean body.

Step 9 Create a blank solid extrusion through the fattened Boolean body, and perform a Boolean subtraction of the blank solid over the fattened body. The body generated from this step becomes the *product model*, which shape should resemble the original CAD model.

Step 10 Perform geometry comparisons between the original CAD model to the product model. This process compares faces and volumes of the reference part (original CAD model) to the modified part (product model). The comparison result is summarized in a report on a hypertext markup language (HTML) format.

The result of geometry comparison can be used to give recommendation on tool manufacturing process ⁽¹⁶⁾. When there are some unprocessed volumes present on the product, undercut volume is highlighted in brown and overcut volume is highlighted in blue. Compensated tool which gives identical product with design model indicate that the tool is valid for orbiting EDM using current orbit path. When some undercut appears on the product model, the compensated tool is still valid for orbiting operation but the undercut need to be removed afterward. Removing the undercut might be executed with 2nd machining operation like static EDM or CNC milling, depending on material hardness and intricacy level or location of the undercut. If overcut takes place, the tool cannot be used for orbiting EDM with current orbit type. The tool has to be re-designed using another orbit path and once again tested for its validity. Fig. 7 depicts tool validation steps for the processed model.

Moving the tool in an orbit path creates secondary removal of workpiece block which volume and surface area depends on the type of orbit applied. Compensated tool presented in Fig. 6 may give different product cavity when using different orbit type. Fig. 8 illustrates product cavities created by compensated tool presented in Fig. 6. First cavity is created by square orbit path, which gives identical geometry as per design requirement, and the second cavity is created using round orbit path. It can be seen that employing round orbit with this tool is failed to produce sharp corners but rounded instead. The corner radius of the cavity produced equals to orbit gap value.

3.3 Automation in CAD

The proposed tool design process and validation is developed as an intelligent tool inside SolidWorks through the use of its Application Programming Interface (API). API is a language and message format used by an application program to communicate with a program that provides services for it. The APIs are implemented by writing function calls in the program, which provide the linkage to the required subroutine for execution. In SolidWorks, the API is written in Visual Basic language with Microsoft Visual Basic for Application (VBA). Microsoft VBA is a toolset based on Microsoft Visual Basic 6.0 and is

Fig. 7 Simulation of orbiting EDM using the *PhysicalTool* to make a product model

embedded inside SolidWorks software. It enables automation process by calling SolidWorks functions from the code written on VB application.

The algorithm of tool design, tool validation and geometry comparison of design model and product model is written in SolidWorks API and is executed automatically after inputting all of necessary information needed to process the model. Presented below is the algorithm to generate physical tool for round orbit which follows tool design steps explained in section 3.1.

Fig. 8 Deviated dimension due to incorrect selection of orbit cycle

CompensateRoundOrbit()

Input: *overcut* //machining overcut, mm
gap //orbit gap, mm
length, width, height //workpiece block size, mm
X, Y, Z //coordinate of origin

Set swApp = Application.SldWorks

Set Active Part (*OriginalMold*)

// Step 1 Create an early tool shape

Select plane and create Rectangle (*X, Y, Z, length, width, 0*)

Extrude Rectangle and rename as *BlankMold*

Select *OriginalMold* and *BlankMold* for InsertCombineFeature(*Subtract*)

Rename Combine1 as *EarlyTool*

// Step 2& 3 Calculate orbit vertices and perform Copy&Translate operation

For $\theta = 0$ To 360

Copy&Translate(*gap cos θ , gap sin θ , 0*)

Next θ

For $a = 1$ To a_{max}

Select Body("Body"&*a*)

Next a

// Step 4 Boolean intersection

InsertCombineFeature(*Intersection*)

Rename Combine2 as *CompensatedTool*

//Step 5 Apply uniform offset to generate *PhysicalTool*

Select EDM working faces

FeatureBossThicken(*-overcut*)

Select *CompensatedTool* and *Thicken1*

InsertCombineFeature(*Subtract*)

Rename Combine3 as *PhysicalTool*

Tool design automation is a real saving time since all required tasks are automated in CAD. It also reduces human-errors on tool design process particularly for model with complex features. The developed system has direct output represented in CAD, which is very convenient for subsequent electrode manufacture with CNC operation.

4. Results and Discussion

4.1 Design Performance

In this work, comparison of performance between manual tool design and automated tool design for two mould models presented in Fig. 9 were done. The manual tool design follows non-uniform offset design principle in section 3.1, only that the engineer has to do every step manually. This process covers tool-making, tool validation, and comparison geometry between design model and product model. Design performance was measured by tool design time and how many mouse-clicks that has to be done to create a tool for this model.

The model tested was divided into two parts. First part was processed using linear orbit and second part was processed using round orbit. This model generates two tools for two different orbit passes. Table 1 gives comparison performance of tool design process for this model. Design automation shows a very significant improvement both on time saving and the number of mouse-clicks needed to process a model. Manual attempt spent most of design time for copy and translation procedure since the engineer has to key-in point locations of orbit path one by one. The amount of orbit vertices depends on the type of orbit. Linear orbit has less vertices points hence manual processing is quite fast. However, round orbit requires at least 72 vertices points to create a smooth circular pattern, and this amount significantly increases design lead time. Inputting orbit point locations manually also more prone to human-error, since the points are composed by orbit length relative to the orbit origin, which value changes according to orbit point position.

In the automation process, design processing time for both given models is significantly increased. Huge increment is noticed from the second part of **Model 1** which was processed using round orbit as design time only take around 12% of the time spent for manual design. Automation avoids human error and minimizes user interventions for part modification during tool design process with accurate result.

Table 1 Performance Data

Model	Partition	Performance data	Manual design		Automation		Savings
			Processing	Modification	Processing	Modification	
Model 1	Part 1	No. of clicks	32	14	1	8	80.43%
		Time (min)	6		3		50%
	Part 2	No. of clicks	172	30	1	8	95.54%
		Time (min)	67		8		88.06%

Fig. 9 Automation of tool design process for two orbiting passes

4.2 Experimental Validation

An experiment to verify the effectiveness of the developed method has been executed for **Model 2** with complex features as depicted in Fig. 10. The model contains several geometries with different fillet radius on the corners. The workpiece used was NAK55, which is age-hardened mold steel with a through hardness of approximately 40 HRC, and the tool electrode used was copper alloy (TeCu). The tool for **Model 2** was compensated for round orbit. Conventional method generally uses several tools to complete the production of one mold. However, this method uses the machining advantage of orbiting EDM on using less tool for machining, hence **Model 2** only need one tool to obtain the required geometry.

Table 2 shows the required dimension of **Model 2** and the measurement result of machined workpiece, which shows a close dimension between the required dimensions to the resulting cavity dimensions created by the application of this method.

5. Conclusion

A method for tool design automation for orbiting EDM was developed in this study. The design concept is based on non-uniform offset of the tool towards a particular orbit path to get an identical product as per design requirement. Manual design of tool for complex shapes takes up a substantial amount of processing time and prone to human failure. To excel these difficulties, an automation of tool design is developed inside CAD tool. The intelligent tool is able to design tool for orbiting EDM directly from CAD model and validates the tool for orbiting EDM process.

Physical tool

Machined workpiece

Table 2 Measurement result

No.	Design (mm)	Measured (mm)
1	40	40.009
2	100	100.011
3	30	29.995
4	40	39.998
5	7	6.941
6	7	6.985
7	7	6.952
8	7	6.991
9	7	6.956
10	7	6.989
11	7	6.953
12	7	6.991
13	7	6.949
14	5	5.009
15	5	4.997
16	5	4.989
17	5	5.004
18	3	3.159
19	3	3.010
20	3	2.905
21	3	3.025

Fig. 10 Method implementation to complex feature

Automation of tool design for orbiting EDM is capable of compensating tool with various geometries simultaneously in much shorter time than manual design. The automation also reduces human errors when facing a concurrent compensation of machining overcut and EDM orbit for a particular geometry. Implementation of tool design principle and automation developed in this work revealed that the physical tool created with this method is able to create accurate dimensions with a single tool electrode. Furthermore, the integration of the developed automation design algorithm with commercial CAD system makes an effortless design transfer for subsequent fabrication process of the tool electrode.

References

- (1)Ferreira, J.C., Mateus, A.S., and Alves, N.F., Rapid tooling aided by reverse engineering to manufacture EDM electrodes, *International Journal of Advanced Manufacturing Technology*, Vol. 34 (2007), pp. 1133-1143.
- (2)Cheng, X., Wang, Z.G., Kobayashi, S., Nakamoto, K., and Yamazaki, K., Tool fabrication system for micro/nano milling -- function analysis and design of a six WEDM machine, *International Journal of Advanced Manufacturing Technology*, Vol. 46 (2010), pp. 179-189.
- (3)Liu, K., Lauwers, B., and Reynaerts, D., Process capabilities of MEDM and its applications, *International Journal of Advanced Manufacturing Technology*, Vol. 47 (2010), pp. 11-19.
- (4)Guitrau, E.B., *The EDM Handbook*, (1997), Hanser Gardner Publications.
- (5)Bamberg, E., and Heamawatachanani, S., Orbital electrode actuation to improve machining efficiency of drilling micro-holes by micro-EDM, *Journal of Material Processing Technology*, Vol. 209 (2009), pp. 1826-1834.
- (6)Egashira, K., Taniguchi, T., Hanajima, S., Tsuchiya, H., and Miyazaki, M., Planetary EDM for micro-holes, *International Journal of Electrical Machining*, Vol. 11 (2006), pp. 15-18.
- (7)Staelens, F., and Kruth, J.P., A Computer Integrated Machining Strategy for Planetary EDM, *CIRP Annals - Manufacturing Technology*, Vol. 38(1989-1), pp. 187-190.
- (8)Sriani, T., Nakamura, Y., and Aoyama, H., Novel Tool Design Method for Orbiting Electrical Discharge Machining, *Journal of Advanced Mechanical Design, Systems, and Manufacturing*, Vol. 4 (6-2010), pp. 1182-1191.
- (9)Yoshida, H., *Die processing technology* (in Japanese), Nikkan Kogyo Shinbusha, (1984), pp. 82-84.
- (10)Dimla, D.E., Hopkinson, N., and Rothe, H., Investigation of complex rapid EDM electrodes for rapid tooling applications, *International Journal of Advanced Manufacturing Technology*, Vol. 23 (2004), pp. 249-255.
- (11)Ferreira, J.C., A study of die helical thread cavity surface finish made by CuW electrodes with planetary EDM, *International Journal of Advanced Manufacturing Technology*, Vol. 34 (2007), pp. 1120-1132.
- (12)Nagahanumaiah, Ravi, B., and Mukherjee, N.P., An integrated framework for die and mold cost estimation using design features and tooling parameters, *International Journal of Advanced Manufacturing Technology*, Vol. 26 (2005), pp. 1138-1149.
- (13)Fleischer, J., Deuchert, M., Ruhs, C., Kuhlewein, C., Halvadjisky, G., and Schmidt, C., Design and manufacturing of micro milling tools, *Mycrosystem Technology*, Vol. 14 (2008), pp. 1771-1775.
- (14)Kechagias, J., Iakovakis, V., Katsanos, M., and Maropoulos, S., EDM electrode manufacture using rapid tooling: a review, *Journal of Material Science*, Vol. 43 (2008), pp. 2522-2535.
- (15)Sohani, M.S., Gaitonde, V.N., Siddeswarappa, B., and Deshpande, A.S., Investigations into the effect of tool shaped with size factor consideration in sink EDM process, *International Journal of Advanced Manufacturing Technology*, Vol. 45 (2009), pp. 1131-1145.
- (16)Pellicer, N., Ciurana, J., and Delgado, J., Tool electrode geometry and process parameters influence on different feature geometry and surface quality in EDM of AISI H13 steel, *Journal of Intelligent Manufacturing*, (2009), doi:10.1007/s10845-009-0320-8.