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The Application of Wire Electrical Discharge Machining (WEDM) in the Prototyping of Miniature Brass Gears

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Abstract

Due to its ability to cut complex shapes without the set-up times of conventional processes, wire electrical discharge machining (WEDM) lends itself to the prototyping or limited-run production of miniature gears with a low aspect ratio for use in small mechanisms. Cutting of very thin workpieces using WEDM presents a difficulty in terms of machining stability, and requires careful consideration of machining parameters.

The recast layer that occurs in WEDM affects both the geometrical accuracy and hardness properties of the gears. For accurate motion transmission, this layer should be minimised. At the same time, the process should be optimised to produce gears in the minimum possible machining time. The production of very accurate, low aspect ratio gears is difficult in WEDM because the limited area for spark generation between wire and workpiece leads to unstable machining, resulting in poor machining rate and surface finish.

This work focuses on reducing the depth of the recast layer and optimising surface finish whilst maintaining an acceptable machining rate. The effects of machining parameters have been investigated, establishing the suitability of the WEDM process for producing gears and gear dies. It is demonstrated that the R_a value for surface roughness in very thin workpieces can be reduced by approximately an order of magnitude (from 3.4μm to 0.4μm) using control of basic parameters.

Building on this, a feasibility study has taken place cutting brass gears of a thickness of 0.3mm and altering rough and skim cut parameters such that the final depth of recast layer is minimised and a smooth surface finish is achieved. The gears were examined for recast layer depth and surface finish. The recast layer was investigated by polishing and etching, then measuring the depth using optical microscopy and a scanning electron microscope (SEM). SEM was also used to investigate surface topography, as different topographies are preferable from a tribological point of view.

The results indicate that the depth of the recast layer can be reduced while maintaining a good material removal rate, by removing only the recast material with the second pass. Thus it is possible to increase the productivity of gear production with WEDM, while maintaining good surface characteristics. This work opens up possibilities for prototyping miniature gears.

Keywords: WEDM; White layer; Recast layer; Miniature gears; surface integrity

1. Introduction

Wire electrical discharge machining (WEDM) is capable of producing intricate parts with high dimensional accuracy and excellent surface finish without the need for post-processing. As a result, it is widely used in the dental, medical and jewellery industries, and to machine materials that are considered difficult-to-machine by conventional processes [1].

These characteristics make WEDM a candidate for producing parts that require little or no finishing or polishing. Furthermore, minimal set-up times make it a very attractive method for prototyping complex geometries such as modified gear geometries[2].

There is extensive literature focused on optimising the surface finish (SF) and material removal rate (MRR) in WEDM. As material is removed by melting small regions of the workpiece, pulse energy is the most important factor affecting surface finish in WEDM. This is influenced by machining parameters such as discharge current, gap voltage, pulse duration, pulse-on time and peak current. Pulse energy, E, can be described as

$$E = \int_0^{t_0} u(t)i(t)dt \qquad (1)$$

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where t_0 is discharge duration, $u(t)$ is discharge voltage and $i(t)$ is discharge current.

To produce prototype gear forms or gear dies using WEDM, it is necessary to achieve an excellent surface finish and high profile accuracy. One of the critical factors influencing surface finish in WEDM is an area referred to as the recast layer. This layer of material has been structurally modified by heat and is often harder and more brittle than the base material [3], reducing the fatigue strength and altering the wear properties of the part [4]. Since fatigue strength and wear are both significant for gears, and indeed for dies used for cutting gears, recast layer is also an important response factor to be measured.

The use of rough cuts followed by skim cuts is frequently employed to achieve a fine surface finish [5]. The rough cut will employ a higher pulse energy to cut the rough geometry, and skim cuts with a reduced pulse energy yield the desired surface finish. It has been suggested that with the appropriate machining parameters, the skim cut can be used to remove solely recast material and not base material [6]. This could enable a rough cut with a relatively short machining time to be used, thus maximising productivity.

Hobbing and stamping are the traditional methods used for manufacturing small gears, and the field of miniature gear production using WEDM is relatively small [7]. Research into miniature gear production has yielded successful production of miniature gears. Typically, gears produced have had a high aspect ratio. This can improve surface properties due to increased stability of machining [8], i.e.the reliable bridging of the gap with appropriate spark energy [9,10] . WEDM's capability to produce very thin parts has been explored less thoroughly, and is likely to be more challenging due to the reduced cross sectional area between workpiece and wire across which a spark can bridge the gap [8].

This work identifies the optimal parameters for achieving a high rate of rough cut machining, while maintaining a good surface finish and the thinnest possible recast layer. Initial trials were carried out before designing the experiment, to select desirable parameters for both the rough and skim cuts.

2. Eperimental Procedure

A standard WEDM (Mitsubishi MV400) was used to machine the parts, using de-ionised water as a dielectric. Due to the capability of the machine used, the smallest wire diameter that could be used was 0.25mm. This limited the minimum size of gear that could be produced and thus gears of 10mm outside diameter (OD) with 18 teeth were produced, with a module of 0.5. The gears had an involute profile and were cut from 0.3mm thick CuZn38 brass.

A full factorial experiment was designed with mid points (Table 1), with the factors being rough cut parameters and offset for skim cut parameters. Three rough cut parameter sets were used, as detailed in Table 2. Two offset values were used for the skim cut, 100 and 140, as well as two mid-point measurements at an offset of 120.

Following machining, the gears were cleaned using a standardised procedure before observation with a 3D non-contact profilometer (Alicona G5) microscope to determine surface roughness, and then mounted, polished and etched so that the recast layer could be analysed b SEM.

Table 1. The Full Factorial Experimental Parameters

Gear Number	Run Order	Rough Cut Parameter Set	Finish Cut Offset
GM5	1	Set 1	100
GM7	2	Set 3	100
GM4	3	Set 3	140
GM8	4	Set 3	140
GM3	5	Set 3	100
GM6	6	Set 1	140
GM1	7	Set 1	100
GM10	9	Set 3	120
GM2	10	Set 1	140
GM9	8	Set 1	120

Table 2. The three rough cut parameter sets used

Rough Cut Parameter Set	Peak Current (t)	Offset (t)	Feed Rate (t)
Set 1	7	175	0.2
Set 2	10	190	0.2
Set 3	13	205	0.2

Two-way analysis of variance (ANOVA) was then used to determine how the rough cut parameters could be modified in conjunction with skim cut offset to achieve a high material removal rate and good surface finish.

3. Results and Discussion

3.1. Effects of Parameters on Recast Layer

The recast layer has a finer micro structure compared to the base material, as can be seen in Figure 1. This easily-identified layer was measured for thickness. It was measured in three places on the tooth - tip, flank and root (see Figure 4). For the roots of the teeth, it was found that neither offset or rough cut parameter set yielded a statistically significant difference. Mean recast layer depth for this part of the tooth ranged from 1.77µm to 3.37µm, which is comparatively very low.

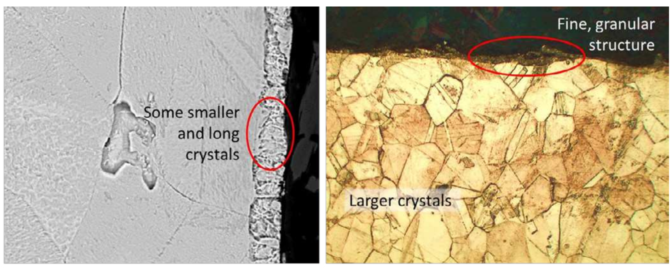

Fig. 1. (a) an SEM image of the smaller grains in the recast layer; (b) an optical image of the same.

For the flanks of the teeth, it was found that the rough cut parameter set is significant, and suggested that the smallest recast layer depth could be achieved using the most agressive parameter set (set 3) and the smallest offset - indeed, a larger offset was not desirable. For the tip of the teeth, there was once again no statistically significant change in recast layer thickness. However, this time the ANOVA suggested that both a higher offset and faster rough cut set improved the recast layer thickness. This is explored further in Section 3.4. When recast layer from the finish cut was compared with that of the rough cut, it was noted that for a more aggressive rough cut, a greater proportion of the recast layer produced was removed by the skim cut, while a lower offset was optimal. It is likely that a higher offset resulted in cutting of base material rather than just recast material. The variation of white layer thickness across all gears was evaluated. To maintain the most constant white layer depth and lowest standard deviation, parameter Set 1 and a small offset should be used.

3.2. Effects of Parameters on Surface Finish

R_a, R_q and R_z values were used to assess surface finish as these are easily comparable with other literature in the field. The surface topography of the parts was of the classic cratered texture that is typical of WEDM parts.

The best surface finish (lower $R_{a,q,z}$values) was seen at the base of the teeth (see Figure 2), and since an excellent surface finish is desirable, this is where measurements were taken. A minimum R_a of 0.37μm was achieved, and 0.46μm and 1.30μm for R_q and R_z respectively. These are comparable to that achieved using multi-stage finishing processes [11] and compare favourably to gears produced only using WEDM [12], although it is a slightly rougher surface than can be achieved by hobbing (which was a maximum of 1μm) [13]. Contrary to recast layer depth, skim cut offset had the most significance in minimising surface roughness.

For R_a, offset was the most important parameter, and increased offset resulted in a higher R_a value. This is similar to the result seen for recast layer thickness in that increased offset resulted in increased recast layer thickness. It is desirable to reduce offset such that only the white layer from the rough cut is removed, and not base material.

For R_q, once again, offset was the most significant of the factors influencing surface finish. As offset was increased, the surface became rougher; however a more aggressive rough cut set did not seem to cause a higher R_a value. Furthermore, rough cut parameters were not significant in influencing R_q, because the finish cut largely determines surface finish of the final part. This is a useful result, as it enables more aggressive (and hence faster) rough cut sets to be used with no detriment to R_q.

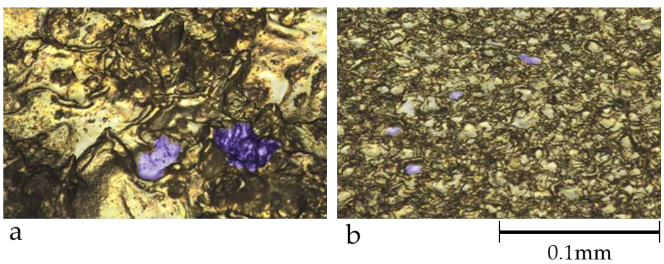

Fig. 2. (a) an example of the large irregular crater-like surface finish seen at the base of the teeth after the initial rough cut; (b) smaller and more regular craters visible after the finish cut (highlighted).

As with the other R-values, R_z was only significantly affected by the offset used for the finish cut. Increased offset resulted in a rougher surface. This is because for offset values which are similar to spark gap size, the finish cut surface and rough cut surface constructively interfere to give a smoother finish. A larger offset instead generates a new surface. Rough cut Set 3 (the most aggressive) resulted in the best surface finish (although this was not significant). The optimal parameter sets were parameter set 3 and an offset of 100.

In order to look at the consistency in the roughness across the entire gear, the variance of R_z was evaluated. Increased offset resulted in a less consistent value, and more aggressive rough cut sets appeared to have no negative effect. Since the lubrication and tribological behaviour of small gears depends heavily on the surface finish, it is very important that this is consistent and so variation should be minimised. As with R_a, R_q and R_z, the optimum result (i.e. least variation) was achieved with an aggressive (fast, high pulse energy) rough cut and low offset (Figure 3).

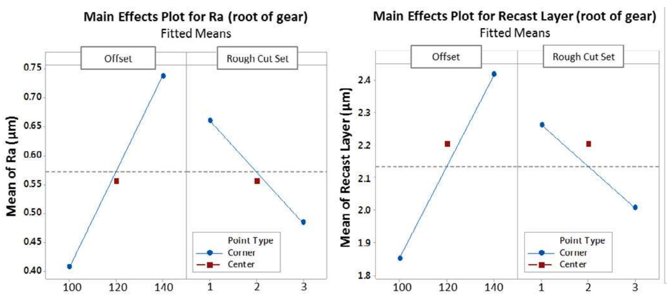

Fig. 3. Main Effects plots show the effect of offset and rough cut parameter sets used on R_a and white layer depth.

In terms of overall improvement in surface finish between rough and finish cuts, the offset was seen to be most significant. A smaller offset lead to a smoother surface compared to the original. In general, results showed that the finish cut offset can indeed be optimised such that white layer only is removed, and this will allow the white layer depth to be reduced while still maintaining a high machining rate during the rough cut, as has been alluded to in previous work [6].

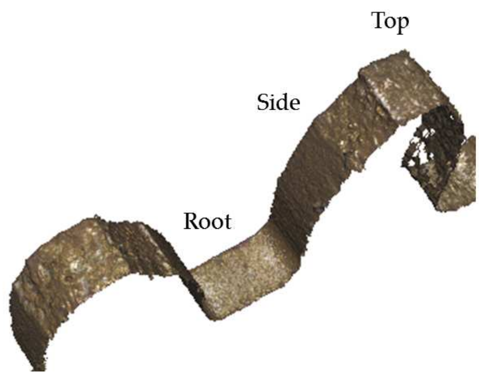

Fig. 4. Varying surface finish across tooth profile can be seen as measured by the 3D non-contact profilometer (Alicona G5).

3.3. Relationship between Recast Layer Depth and Surface Finish

As explained in Section 1, both the white layer depth and surface topography are important in the production of very small gears to achieve appropriate material and lubrication properties. It is therefore important to understand how machining parameters affect both of these, and indeed how they are related. The ratio of recast layer (RL) to Surface finish (Ra, Rz etc) for the base of the teeth is given in Table 3. Generally speaking for the rougher surfaces the white layer was not only thicker in absolute terms, but thicker relative to surface finish. It is clear that for a recast layer thickness, a higher surface roughness in terms of crater size and depth is also seen, i.e. parameters that increase one also increase the other.

Table 3. The ratio of recast layer to surface roughness parameters Ra and Rz was used to indicate relative thickness of recast layer to surface roughness.

Area	Ratio of recast layer depth to Ra	Ratio of recast layer to Rz
Base of teeth	$\frac{RL}{Ra} = 3.94 \pm 1.27$	$\frac{RL}{Rq}$ was 3.21 ± 1.08
Tip of teeth	$\frac{RL}{Ra} = 2.00 \pm 0.56$	$\frac{RL}{Rq} = 1.64 \pm 0.51$

3.4. Notes on Recast Layer Depth and Surface Finish across Tooth Geometry

It was observed that the surface finish achieved (and indeed recast layer depth) was inconsistent across the entire tooth profile. This can be seen in Figure 5.

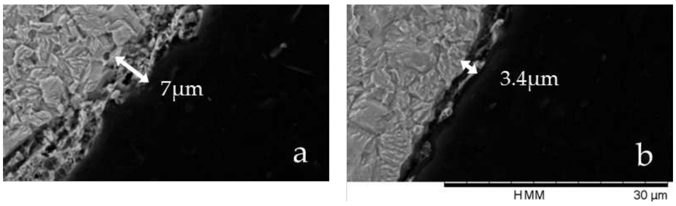

Fig. 5. (a) recast layer depth for the tip of a tooth (seen as smaller grains in a slightly darker shade of grey); (b) recast layer depth for the root of a tooth.

This phenomenon was seen for all gears, and has two physical explanations. The first relates to radius of the wire path. It can be assumed that spark energy is constant and thus each spark produces an identical sized crater, perpendicular to the workpiece surface. For a greater path radius (i.e. flatter path) with the same feed rate, the craters overlap less which results in a higher peak between craters (Figure 6).

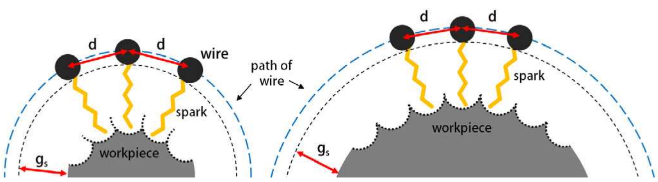

Fig. 6. (a) recast layer depth for the tip of a tooth (seen as smaller grains in a slightly darker shade of grey); (b) recast layer depth for the root of a tooth.

The second explanation relates to the smoothness seen at the root inner radii (between the root and flank). Here, the wire is surrounded by material and there is much more opportunity for sparking and thus machining is more stable. On outer corners such as the tip of the teeth, there is very little opportunity for sparking which leads to unstable machining and a rougher surface as well as more random crater geometries. The result is that wire feed rate should be slower for the tips of gears and external corners, which is significant for MRR.

4. Conclusions

- In terms of white layer, the rough cut parameter set is significant, but an aggressive rough cut combined with a smaller offset achieves a desirable thickness.
- Regarding surface finish, rough cut parameters set is insignificant within the bounds investigated, which allows a fast (or more aggressive) rough cut parameter set to be used and speeds up machining time.
- The tool path radius of the wire had an effect on the surface finish, thus parameter control is required such that pulse energy is reduced in these areas.
- Using the premise that wire offset and finish cut parameters have the most significance when determining surface roughness and recast layer thickness, it is possible to have a fast rough cut while minimising these so that machining rate is higher and quality is adequate.

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