Improvement of Mechanical Fatigue Life of Tool Steel with Electrochemical Finishing

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Degraded surface integrity has long been recognized as a major contributing factor to premature die and mold failure due to mechanical fatigue. To avoid distortion, complex die and mold surfaces are often finish–machined after heat treating by electrodischarge machining (EDM), which typically results in a brittle surface recast layer. This layer acts as an initiator for fatigue cracking. Here we report on recent work to extend tooling life by improving the integrity of AISI H–13 hot work tool steel by applying pulsed electrochemical machining (PECM) to tool steel specimens after EDM. Specimens are mechanically fatigue tested to failure, and compared to identical samples given other surface treatments. Significant improvement in fatigue life is achieved by the PECM treatment. Ongoing efforts to further improve surface integrity are expected to show even more promising results.

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Introduction

Although electrochemical machining (ECM) is widely used in the aerospace industry for the production of complex shapes such as turbine blades in difficult–to–machine metals, its use in the tool and die industry has been quite limited. Electrodischarge machining, or EDM, is the dominant production method for machining hardened steel dies and molds, due to its ability to machine complex surfaces to very high tolerances. In contrast, the necessity of using high flowrate electrolyte to remove waste heat and material during ECM, with the consequent loss of precision, has greatly limited ECM's usefulness in fabricating one–of–a–kind dies and molds. ECM is much more useful when a large number of identical parts must be machined.

Since its introduction in the early 1980's, pulsed electrochemical machining (PECM) has been suggested as a possible method for polishing the surface of dies and molds machined by EDM[1]. Although EDM affords the tool or die maker the ability to machine hardened steel in intricate detail, it also results in the formation of a brittle recast layer that leads to reduced mechanical and thermal fatigue life[2–5].Because PECM uses the finishing EDM tool, it offers the possibility of bringing the surface to a high finish under controlled conditions that maintain the surface geometry within very precise tolerances. Very recently, EDM and PECM operations have been combined into a single machine tool [6].

Electrochemical machining (ECM), as compared to EDM, is a relatively high removal rate process that involves anodic dissolution of the workpiece in a neutral electrolyte. Because ECM is electrolytic rather than thermal, it is known to result in little or no residual stresses on the machined surface[6,7]. Pulsed ECM has the further advantage of dissipating waste heat and reaction products between erosion pulses, thus avoiding the problems associated with applying ECM to tool and die machining.

Little research has been reported to date on the effect of PECM process parameters on surface finish. Rosset *et al.* reported on the effect of pulse parameters, electrolyte composition, and anode material on three die steels of varying alloy content. Steel specimens 1 cm long and 0.3 cm wide were embedded in epoxy and positioned flush with one wall of a 0.3 cm wide flow channel, with a constant electrolyte flow velocity of 2.5 m/sec. The steel specimens were hand polished to an initial surface roughness of either 0.7 µm R_a or 2 µm R_a, and three different electrolytes, 1M $NaNO_3$, 6M $NaNO_3$, and 4M NaCl, were used [8].

Anodic weight loss and surface roughness were measured, and the anodic weight loss was used to calculate an apparent valence as a function of applied current density for each alloy. The apparent valence for an alloy can be derived from Faraday's Law as

$$n = \frac{Q \; M_{alloy}}{\Delta W \; F} \tag{1}$$

where n is the apparent valence of the alloy, Q is the total charge applied , M_{alloy} is the atomic weight of the alloy, ΔW is the measured weight loss, and F is Faraday's constant. Rosset found that the apparent valence of the steels machined in $NaNO_3$ electrolytes varied between 2.0 and 3.4, depending on the dissolution products assumed to be formed (Fe^{2+}, Fe^{3+}, Cr^{3+}, Cr^{6+}). A strong dependence of surface roughness on current density was also observed for the steels machined in the $NaNO_3$ electrolyte.

Very recently Klocke and his colleagues have published an important paper on pulsed ECM in combination with EDM[6]. The apparatus employed by Klocke's group combines EDM and PECM in a single machine, which has the obvious advantage of maintaining precise alignment between tool and workpiece.

The experiments were performed on 56 NiCrMoV7 steel (comparable to AISI H–11) machined by a graphite EDM electrode in a 50%

water/50% glycerine dielectric to a 7 μm R_a surface finish. The pulse duty factors used were 20/100 and 50/100, at a gap voltage of 24 V, in NaCl and $NaNO_3$ electrolytes with a gap width of 0.5 mm.

A fairly linear relationship between electrolyte concentration and removal rate was observed in these experiments, which would be expected. However, Klocke's group found that surface roughness tends to first improve and then degrade with total pulse duration for both passivating and non–passivating electrolytes, leading to the conclusion that an optimum value of polishing time exists for this process.

Finally, data for residual stress and mechanical fatigue of specimens prepared by EDM and PECM is presented. Klocke found, in agreement with earlier work[4] that tensile residual stresses due to EDM reach a maximum value at 10–20 μm depth, while specimens prepared by PECM showed essentially no residual stress. A marked improvement in fatigue life for specimens polished by PECM following EDM treatment is also shown, which is presumably due both to a removal of residual stress and an improvement in the surface finish.

Previous work by the authors investigated the effect of PECM on the mechanical fatigue life of H-13 steel [9]. We found that, as expected, specimens that were eroded by EDM and subsequently polished with PECM showed an improvement in fatigue life, as compared to specimens subjected to EDM without subsequent polishing. We attributed this improvement in the fatigue life to the removal of the surface damage due to EDM, notably the brittle, heavily microcracked recast layer.

Our earlier work, however, did not attempt to improve the PECM surface finish by varying the combinations of the applied pulse parameters. One primary advantage of pulsed, as opposed to conventional, ECM is the increased control it provides the user through the added parameters.

The specimens in the previous work were subjected to relatively high energy EDM, and were then polished using single current pulses of 20 msec duration, with an average current density of 100 A/cm^2, and an initial machining gap of 80 μm. While this surface treatment was adequate for removal of the EDM damage, the surface created by the PECM process was not satisfactory. Extensive pitting of the surface was observed, which led to the conclusion that better fatigue life would result if the polishing process could be improved through more intelligent use of the pulse parameters.

Experimental Procedure

The work reported on here is a continuation of our investigation of PECM as a polishing method for die and mold surfaces. This work consisted of several phases. In the first phase, several specimens of H–13 were subjected to an EDM treatment that resulted in a surface finish of approximately 4 μm R_a. This surface finish was thought to be typical for general purpose die and mold making, and is comparable to the 7 μm R_a finish employed by Klocke et al.

These specimens were then cross–sectioned and metallographically prepared in order to determine an average depth of recast layer. The typical sample shown in Figure 1 clearly shows that the recast layer thickness varies over a fairly wide range, but rarely exceeds 25 μm.

The next step was to determine the level of PECM polish that would ensure the total removal of the recast layer., Faraday's Law states that the mass of metal removed is directly proportional to the charge applied. A series of experiments were conducted to determine the charge density needed to assure removal of the 4 μm R_a recast layer. It was determined that 300 C/cm^2 resulted in a surface completely free of EDM recast.

Following these experiments, a two-level, four factor experimental array was used to determine the main and interaction effects of the principal pulse parameters on both the surface finish and the metal removal rate. Pulse on–time, pulse duty factor (on–time divided by total pulse time), current density, and number of pulses in a pulse group were chosen as the most likely parameters. Based on our own previous work, and that of other researchers in the field [8,10], we expected to see some significant amount of interaction among the pulse parameters.

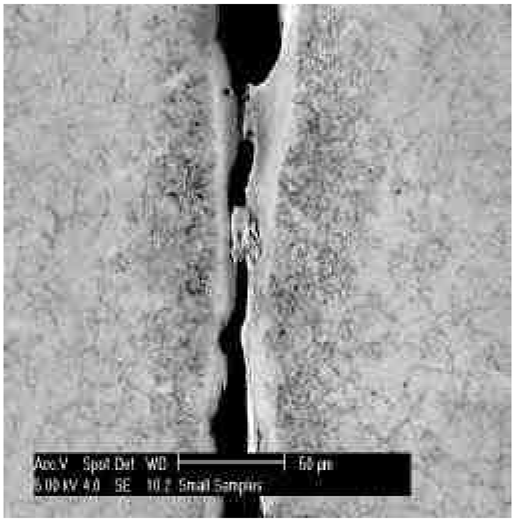

Figure 1: Recast layer, 4 µm R_a EDM Surfaces

The PECM experiments were performed on a Shizuoka Seiki COTAC 51 machine, which is capable of polishing workpieces having a surface area up to 300 cm^2, in a 40% $NaNO_3$ electrolyte, with a maximum power of 5.5 KVA. Further details are given in[11]. It should be noted that constraints imposed by the machine controller limited to some extent the choice of parameter levels. For example, previous research[12,13] has shown that 1 ms or shorter pulses can often give a superior surface finish. However, in this case use of such short pulses caused the total number of pulses necessary for a total charge of 300 C/cm^2 to exceed the maximum permitted by the machine control. For this reason, the levels chosen for pulse on–time were 5 and 10 ms, which admittedly are not optimal. Table 1 shows the parameter settings for the first set of experiments.

The PECM tools used in the experiments were machined from high-grade copper, ground and polished to a 0.5 µm R_a finish. Although the electrode periodically retracts to permit flushing of the surface by the electrolyte, it returns to the initial electrode position throughout the machining cycle, which for these experiments was chosen to be 80 µm. It is important to note that the electrode does not "chase" the workpiece surface as it erodes; as the workpiece dissolves, the machining gap increases. Because the COTAC uses constant current control, the controller compensates for the increased resistance across the machining gap by increasing the applied voltage during the machining cycle.

Following this set of experiments, a second set of eight two–level, four factor experiments was conducted in the region of the parameter space giving the best surface finish as determined by the screening tests. The results of these experiments are presented below.

Table 1: Initial Parameter Settings

Parameter	High	Low
Current Density (A/cm^2)	50	30
Pulse on–time (msec)	10	5
Duty factor (%)	3	1
Pulses/group	15	5

A secondary goal of the experiments was to measure the effect of the parameters on the metal removal rate. Due to the presence of passivating layers on the surface of the samples, weight loss as a method of estimating metal removal was felt to be unreliable. Instead, a surface profilometer was used to estimate the amount of metal removed.

On each specimen, a small section of the surface was shielded from the erosion current by the fixture, remaining unpolished by the PECM process. By positioning the specimen so that the profilometer trace began in the unpolished area of the surface, and then tracked onto the eroded surface, an estimate of the amount removed could be obtained. For these measurements the surface parameter, W_t, which is a measure of surface waviness, was used. For each specimen, three different profiles were recorded, and the mean value of W_t was recorded as the removal depth.

Based on these experiments, a new set of parameters was then used to polish 24 fatigue specimens, following a 4.0 R_a, EDM treatment using a rotating copper electrode in a hydrocarbon dielectric. As in our earlier work, premium–grade AISI H-13 steel was chosen as the specimen material, due to its wide use in the US die and mold making industries. The specimens, designed according to the ASTM standard E466–82, were machined by wire EDM from a single block of H–13 steel after heat treating to a final Rockwell "C" hardness of 46–48, a typical hardness condition for die casting dies. NADCA standards for premium–grade H–13 were applied in heat treating. Details of the specimen geometry is given in [Lilly, 98].

Experimental Results

Parameter Optimization

As a result of the initial screening tests, it was found that a strong interaction effect existed between pulse on–time and current density, as well as between on–time and duty factor. Based on these results, a region of the parameter space likely to give optimum results was selected, and a further set of experiments was conducted.

This set of experiments varied duty factor and pulse on–time in a region around the values T_{on} = 5 ms, with duty factor = 2.2%. The current density for these tests was held constant at 40 A/cm^2, which was felt to be a reasonable value, based on the previous set of experiments.

Response surfaces were generated using the surface parameter, R_a, and the metal removed, as estimated by W_t, as the dependent variables, and the pulse on–time and duty factor as independent variables. The response surfaces are shown in Figures 2 and 3. These two parameters dominate the results obtained, and appear to be the most important in determining surface finish and removal rate.

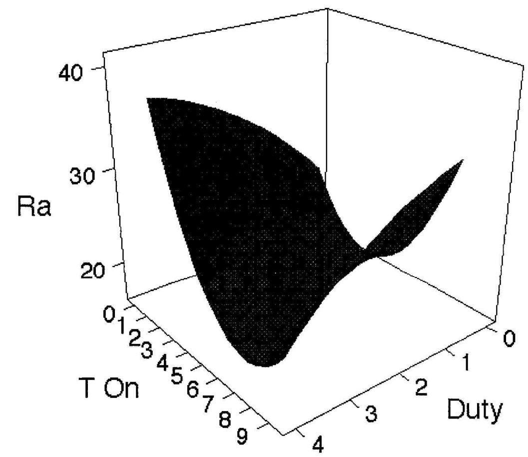

Figure 2: Response surface for surface finish

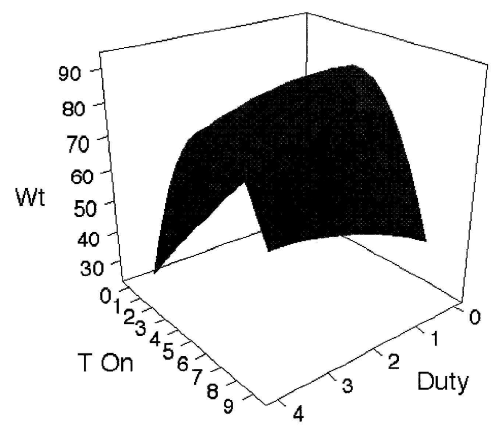

Figure 3: Response surface for metal removal rate

Based on the results of these experiments, the set of pulse parameters used to polish the fatigue specimens was obtained. However, experience showed that the uninterrupted use of these parameters for long periods of time invariably resulted in the surface of the workpiece becoming covered with a black, passivating layer. It was found that by alternating 50 groups of five, 5 ms pulses with twenty–five single 20 msec pulses, which removed most of the black layer, good results could be obtained. This variable–pulse length polishing method that was then applied to the fatigue specimens.

Mechanical Fatigue Tests

In order to establish a baseline against which the effect of PECM could be measured, a series of mechanical fatigue tests were conducted on H–13 specimens with a variety of surface treatments, including high–energy EDM, multiple–energy level EDM, and surface grinding. Some of these experiments were reported on in [Lilly, 97]. In these experiments, it was determined that specimens polished using single PECM pulses of 20 ms duration showed some improvement over specimens left in the as–EDM'd state. However, the surface finish obtained with these long single pulses was far from optimum.

One of the primary goals of the current series of fatigue experiments was to determine what, if any, effect an improved surface finish would have on the fatigue life of the specimens. Accordingly, a group of 25 specimens were finished by PECM to a 2 µm R_a surface finish using the improved polishing parameters, following an initial EDM treatment to a 4 µm R_a finish. These specimens, designated as PECM-II in Figure 4, were then tested to failure and compared to the earlier group subjected to the 20 ms pulses (PECM-I). The results shown in Figure 4 confirm that the improved surface finish of the second group clearly resulted in longer fatigue life.

Along with this group of specimens, a second set of 25 specimens was subjected to an EDM erosion cycle resulting in a comparable (~2 µm R_a) surface finish. These specimens were also tested and compared to the group receiving the PECM–II treatment. Finally, a third group of 25 specimens was finished by surface grinding (along the axis of the fatigue specimens) to approximately the same surface finish, and also tested to failure.

The fatigue behavior of these three groups is shown in Figure 5. From these results it seems clear that the specimens that were finished with the improved PECM treatment show a marked improvement in

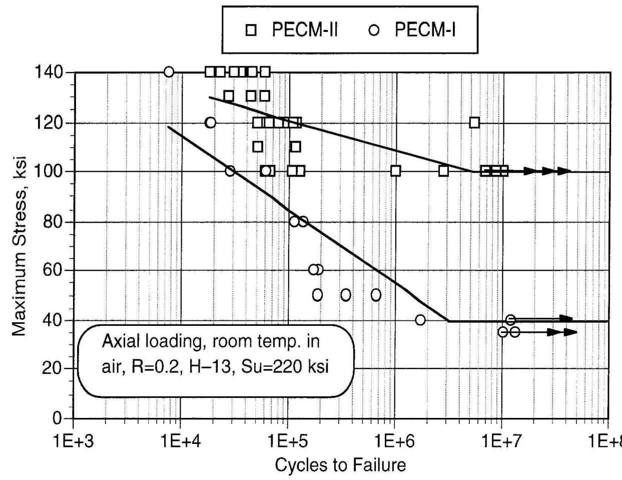

Figure 4: Fatigue behavior of H–13 steel after PECM

fatigue life, as compared to EDM specimens with a comparable surface finish.

However, it is also clear that the specimens treated with PECM–II did not perform as well as those that were surface ground. A comparison of Figures 4 and 5 also shows that the EDM specimens with a 2 µm surface finish generally outperformed those that were given the original PECM–I treatment.

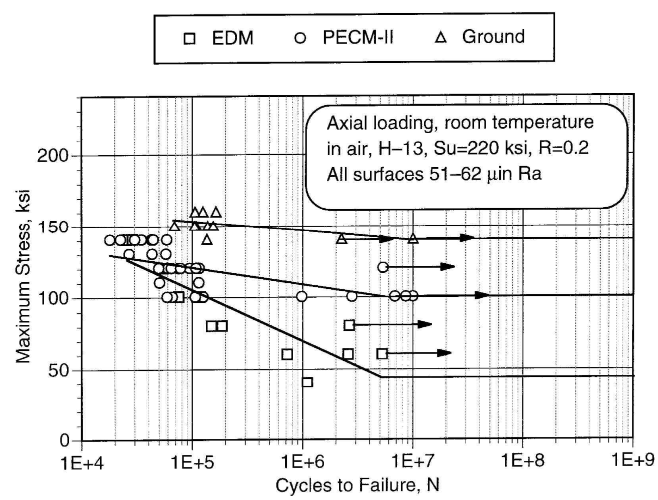

Figure 5: Fatigue behavior of H–13 steel, following EDM, PECM and surface grinding

Based on the recent work by Klocke, as well as earlier work by [Rumyantsev,89], it seems safe to assume that the PECM process results in a surface essentially free of residual stresses. Hence, it would appear that the only remaining factor that could be responsible for the observed degradation in fatigue life would be the nature of the PECM surface itself.

In fact, as the photograph shown in Figure 6 shows, the surface following PECM treatment shows considerable “weathering”, with some clear signs of differential erosion visible. These surface flaws can serve as crack initiation sites, which can lead to early failure in fatigue.

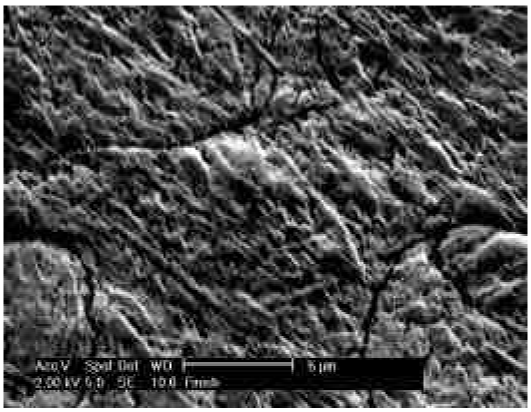

Figure 6: Scanning electron micrograph of H–13 surface following PECM treatment

Further work is needed to determine if a better combination of process parameters can result in a more polished surface, leading to better fatigue life. One clear difference in the work reported here and that due to Klocke *et al*. is the significant difference in initial machining gap. Additional tests using larger machining gaps are clearly warranted.

Additional experiments are currently underway to expand the scope of this initial work, and are reported on elsewhere in these proceedings [14]. We are currently testing additional H–13 tool steel specimens, in addition to stainless steel, inconel, and titanium. We fully expect to see a marked improvement in fatigue life with these metals following PECM treatment.

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