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Meso-Scale High-Strength Metal Clock Plate

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***Abstract* - The phrase “clock plate” refers to the mounting frame of a mechanism that positions pivot pins on which rotatable elements such as wheels, gears, and levers operate. To a large extent, the clock plate determines the precision, strength, and toughness of the entire mechanism. Historically, the term “clock plate” referred to one of a pair of plates fastened by pillars forming a clock frame for a time keeping mechanism, but here clock plate refers to a more general application.**

A new production process for creating high-strength metal clock plates with improved precision for robust meso-scale mechanism products is described. The production method involves a two-stage approach where oversized features were first fabricated by conventional machining followed by micro-wire electrical discharge machining (EDM) to achieve final dimensions and tolerances. After EDM trimming, each pivot pin’s center location, circular contour, and diameter are producible with a tolerance of ±1.5µm. Post-processes such as electropolishing to remove recast layers generated during EDM and application of diamond-like nanocomposite (DLN) coatings to mitigate friction and wear were developed. These post-processes introduced dimensional tolerances, but provided a robust finish with improved tribological (friction and wear) characteristics for the clock plate’s bearing surfaces, significantly improving the clock plate’s performance. Several meso-scale clock plates, machined from a high-strength 21-6-9 stainless steel, were successfully prototyped using this method.

Index Terms - Meso-Scale, Mechanism, Metal, High-Strength, Clock Plate

INTRODUCTION

Small clock plates can be found in watches, medical instruments, sensors, timers, actuators, and other mechanisms where required dimensional tolerances can range from fractions of a millimeter (mm) for miniature-scale devices, microns (µm) for meso-scale devices, to fractions of a micron for micro-scale devices (surface micro-machined silicon). Miniature-scale mechanisms use clock plates that are fabricated from an assortment of metal pivot pins inserted into holes of a metal base plate or mounting frame. The miniaturization possible is limited by the diameter and center location accuracy of the holes along with the diameter accuracy of the pins. The pin insertion step introduces pin perpendicularity and pin height variation, which also limits miniaturization.

Micro-scale mechanisms, employed in Micro Electromechanical Systems (MEMS), use clock plates made of silicon and are formed as one integral part using a lithographic process called Silicon Surface Micromachining to achieve the needed precision. Meso-scale metal mechanisms (smaller than miniature-scale and larger than micro-scale MEMS) provide for a specification niche that can not be filled by either miniature-scale metals or micro-scale silicon.

A meso-scale clock plate design was prototyped using a high-strength, annealed 21Cr-6Ni-9Mn stainless steel (21-6-9 SS, commonly known as Nitronic 40™) with an ultimate strength of 765 MPa, a yield strength of 444 MPa , an elongation at break of 42.5% in 50 mm, and a machinability of 30% based on 100% machinability for AISI 1212 steel. In addition, 21-6-9 SS was selected for its heat resistance and low magnetic permeability. The clock plate’s integral pivot pins were created using a two-step process. First, each pin’s bearing surfaces were conventionally machined in relief to protrude above the base plate with the bearing surface diameter over-sized. Second, these over-sized bearing surfaces were trimmed to a more accurate diameter, perpendicularity, and center-location using a micro-wire EDM process. Front-to-back registration pins extending from both sides of the clock plate are also possible with this method.

The micro-wire EDM cutting process creates a slot with melted part surfaces, which are referred to as the “recast layer.” An electropolishing technique was used to remove the EDM recast layer from the pivot pin’s bearing surfaces, leaving the metal base-material exposed and smoother than the recast layer.

The application of low-friction hard coating on the meso-scale bearing surfaces is also discussed. A 1.0 µm thick Diamond-Like Nanocomposite (DLN) coating applied on EDM prepared electropolished surfaces was evaluated for tribological (friction and wear) behavior.

HISTORICAL PERSPECTIVE FOR SMALL METAL MECHANISM COMPONENTS

A typical miniature-scale clock plate uses precision machined metal pins that are inserted into corresponding drilled holes in a base plate. The pins are typically press-fit and subsequently welded into place as shown in Figure 1.

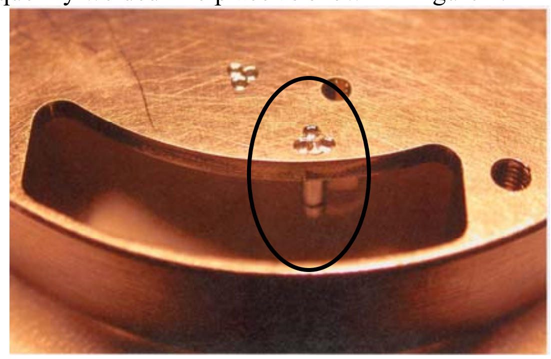

Figure 1 – Typical Miniature-Scale Pivot Pin (0.78 mm diameter) Inserted into Its Corresponding Drilled Hole before Being Welded in Three Places

When scaling down to smaller sizes, the required tolerances become smaller than traditional processes typically can provide. Alternative manufacturing methods are therefore needed.

Meso-Scale machine components, such as the stainless steel ratchet wheel shown in Figure 2, have been created using micro-wire EDM [1].

The production method presented herein provides for forming a precision meso-scale metal clock plate having integral pivot pins with micro-wire EDM-trimmed tolerances on the order of ± 1.5 µm, which is comparable to the ± 0.5 µm obtainable using micro-machining methods such as LIGA, an acronym based on the first letters of the German words for lithography, electroforming and molding (i.e. lithographie, galvanoformung and abformung).

MESO-SCALE METAL PIVOT PIN GEOMETRY

The first process step consists of creating a pin with flats formed in relief from a solid monolithic metal blank using a precision milling machine (see Figure 3). The curved bearing surfaces are created slightly over-sized. Note the fillet produced by the end mill at the base of the pin to reduce the stress concentration. The EDM machine requires a through-hole adjacent to the trim location for passing the EDM wire through the base plate before starting the EDM cut. The milled pin has flats corresponding to spokes that will structurally hold the pin to the base plate. The flats are to keep the milling machined surfaces (lower precision) from conflicting with the EDM-cut bearing surfaces (higher precision).

The second step uses a micro-wire EDM process that trims the bearing surfaces with a precision better than that of the milling machine and eliminates the fillet at the base of the bearing surfaces, while leaving a fillet on the spokes (see Figures 4 and 7).

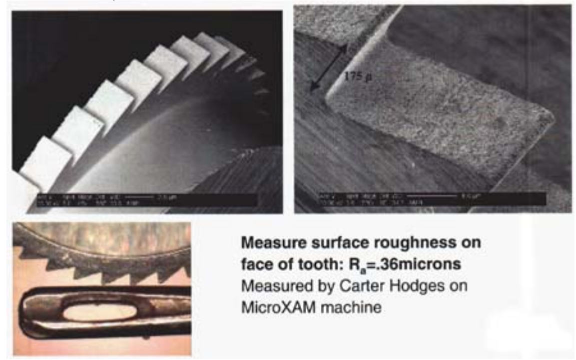

Figure 2 – Meso-Scale Ratchet Wheel with a 175 µm Tooth Height Produced Using Micro-Wire EDM

FRONT-TO-BACK REGISTRATION PINS

Integrated front-to-back registration pins, extending from both sides of the clock plate, can be created using a method similar to that of the pivot pins. One would machine the registration pin features in relief protruding on both sides of the base plate with the bearing surface features over-sized. Both of the misalignments (front-to-back milling machine set-up tolerance and milling machine variation tolerance) are replaced by the finer tolerance of a single and more precise micro-wire EDM trimming process (see Figure 5).

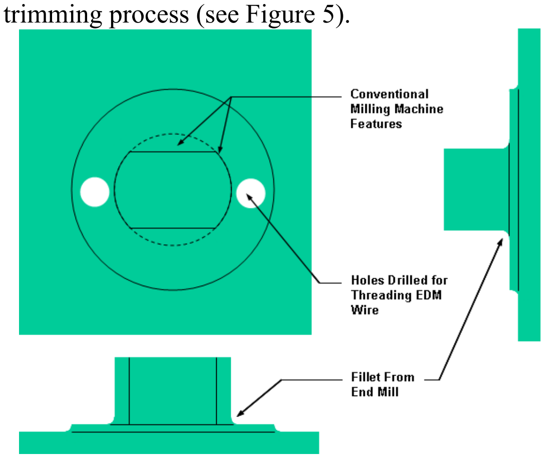

Figure 3 – First Step: Create Preliminary Features Using a Milling Machine

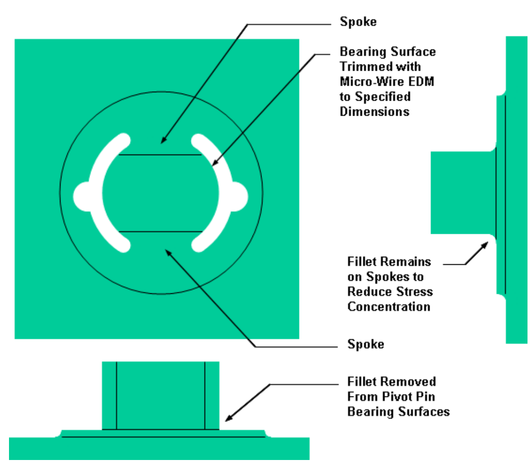

Figure 4 – Second Step: Create an Integrated Pivot Pin by Trimming the Bearing Surfaces with a Micro-Wire EDM Process

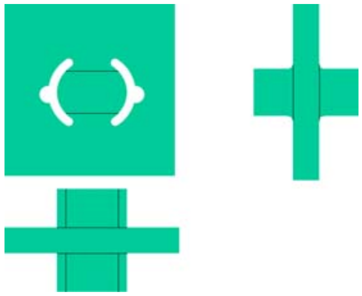

Figure 5 – Front-to-Back Registration Pin Using This Technique

PRECISION MACHINING METHOD FOR THE MESO-SCALE CLOCK PLATE

The meso-scale clock plate prototypes were machined using a 5-axis Willemin-Macodel W-408MTV precision mill-turn machining center. The majority of the features in the clock plate were well within the capabilities of this machine, however, the tightest tolerances were found on the integral pivot pins. These pins needed to be perpendicular to the bottom surface of the clock plate and had tight tolerances for both the diameter (i.e. ± 5 μm) and center position of the pins (i.e. 10 μm maximum radial deviation from true position). Figure 6 shows a model of a pin during milling. Achieving this level of tolerance, while machining 21-6-9 SS, is difficult in a side milling operation as the machining forces (cutting force and thrust force) work to push the tool away from the pin. The cutting force deflects the mill along vector A causing the position of the pin to be incorrect. The thrust force deflects the mill along vector B causing the diameter and cylindricity of the pin to be inaccurate. Because the very small diameter milling tools are essentially cantilever beams, the diameter of the pin is machined smaller at the top of the pin and larger at the bottom of the pin. In addition to this diameter variation, the spinning of the milling tool during cutting causes a tangential cutting force which bends the tool and causes the pin location to be inaccurate as well. Machining trials showed that it would not be possible to achieve the desired diameter and location control, so an alternative method of machining was needed.

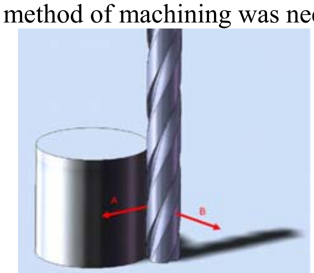

Figure 6 – Small End Mill Deflection along Direction A due to the Cutting Force and Along Direction B Due to the Thrust Force

TWO-STEP PRECISION MACHINING

In order to avoid machining errors, a high-precision, low force method was needed for the creation of the integral pin features. Micro-wire electro-discharge machining (EDM) was selected due to its extremely low cutting forces and its ability to achieve tight tolerances. The micro-wire EDM used for this process is an Agie Vertex 1F running 30μm diameter tungsten wire. The machine is in a temperature controlled, vibration isolated room where it is able to achieve positional accuracies of ±1.5μm. The EDM process uses a wire as an electrode and generates sparks between the wire and the part. Each of these arcs causes the creation of a small plasma plume and the plasma removes a small amount of material from the part. The EDM process has low machining forces due only to the pressure of water that is used to flush out the cutting debris and the very small electrical force that is generated by the electrical field around the wire. EDM is also advantageous because it machines based on the electrical conductivity of a part and machining times are independent of material hardness.

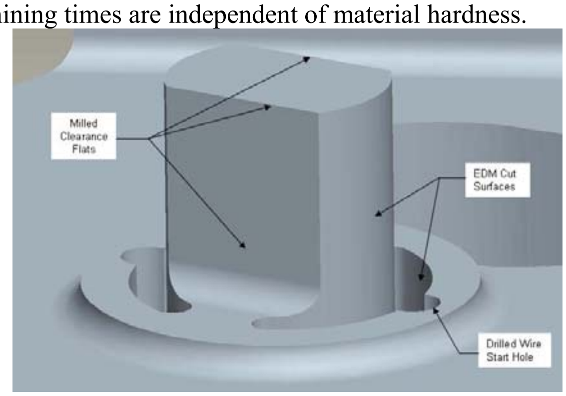

Figure 7 – Meso-Scale Pivot Pin Design Showing the Precise Geometry Created by the Micro-Wire EDM Process

For EDM to solve the clock plate pin tolerance problem, the pin design had to be modified somewhat. Wire EDM uses a continuous wire that must feed all the way through a part. Because of this process requirement, holes were added so that the wire could be fed through the part as shown in Figures 3 and 7. The need for continuous wire also presented a challenge in creating the pin. If the EDM had been used to create the entire pin (by cutting all the way around the pin), the pin would have become detached from the clock plate and would have fallen out. However, the less-precise milling process could be used to machine slightly oversized diameter (≈0.05 mm) bearing surfaces and clearance flats as shown in Figure 3. These flats would not affect the positioning of the component that fits on the pin, and they left 2 sides of the pin that did not need to be machined by EDM. The EDM wire was fed through the start holes, and a semi-circular arc was machined around one side of the pin. The process was repeated on the other side of the pin and the resulting pin had excellent perpendicularity, diameter, and position. The final pin geometry, after the micro-wire EDM process, is shown in Figure 7. This configuration allowed a monolithic pin-on-plate feature to be created with excellent diameter, position, and perpendicularity accuracy.

MESO-SCALE CLOCK PLATE PROTOTYPE

Several clock plates were successfully prototyped using high-strength 21-6-9 SS (see Figures 8, 9, 11 and 12). The clock plate's 15 pins and stop surfaces were integral, therefore reducing perpendicularity and height variation and the need for pin insertion. There was a combination of pivot pins, registration pins, and motion stop surfaces, all requiring high dimensional precision. These critical bearing surfaces were created using the two-step machining process described in the Precision Machining Method section.

The micro-wire EDM cutting process produces a melted surface referred to as the "recast layer" and the roughness or thickness of this layer is a process variable that must be controlled during manufacturing. Figure 9 shows the difference in recast layer roughness resulting during test cuts.

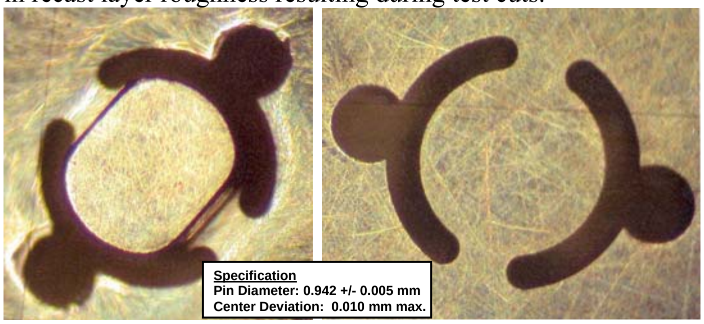

Figure 8 – Top and Bottom Views of Prototyped Clock Plate Pivot Pin with Bearing Surfaces Trimmed by a Micro-Wire EDM Machine

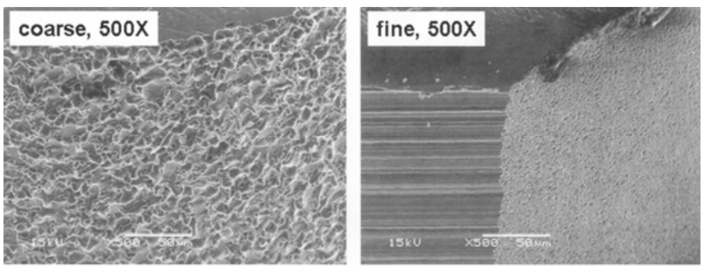

Figure 9 – Micro-Wire EDM Recast Layer Roughness Variation

FRICTION AND WEAR BEHAVIOR OF EDM RECAST LAYER BEARING SURFACES

Friction and wear measurements were performed using a ball-on-disk linear wear tester. A 10 mm square coupon of 21-6-9 SS was prepared by micro-wire EDM process. The test coupon was mounted in such a way that the sidewall of the EDM surface was in sliding contact. The counter-face was a 3.125 mm diameter Si_3N_4 ball. The tribometer was in an environmental chamber with provision to control water vapor and oxygen contents. Measurements were made in air with 50% relative humidity. More complete descriptions of the test procedure are given elsewhere [3].

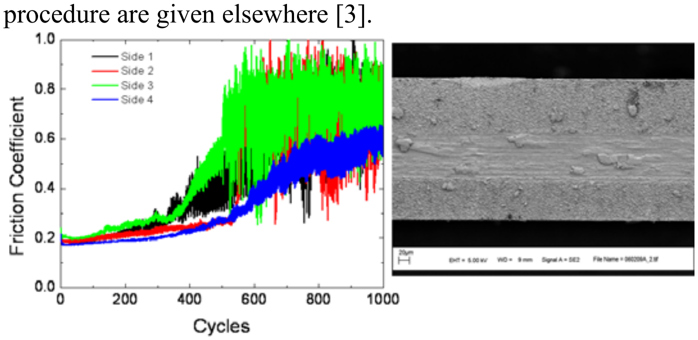

Figure 10 – Friction Behavior of EDM Recast Layer Surface of 21-6-9 SS Alloy

Figure 10 shows the friction coefficient of an EDM recast layer on 21-6-9 SS surface with number of test cycles. The initial friction corresponds to the contact between the recast layer and Si_3N_4 ball. Note that as soon as the recast layer wears away, the friction coefficient increases, exhibiting stick-slip behavior. The SEM micrograph in Figure 10 shows the location of the wear scar in the center of the sidewall.

Stress concentrations at the bottoms of the crevices remain on the recast layer surface (see Figure 9). These crevices will affect the clock plate's fatigue life, so methods for recast layer removal were investigated.

ELECTROPOLISHING THE EDM TRIMMED BEARING SURFACES

After EDM trimming of the clock plate's pivot pins, the bearing surfaces had recast layers as shown in Figures 11 and 12. Electropolishing has been shown to be a practical means of producing the needed surface finish on micro-wire EDM parts for pivot pin applications, besting other options including mechanical polishing, laser-ablating/glazing and micro-abrasion. Electropolishing is a selective dissolution process in which the high points of a rough surface are dissolved faster than the depressions. This inherent characteristic makes electropolishing an ideal method for removing the recast layer produced by EDM.

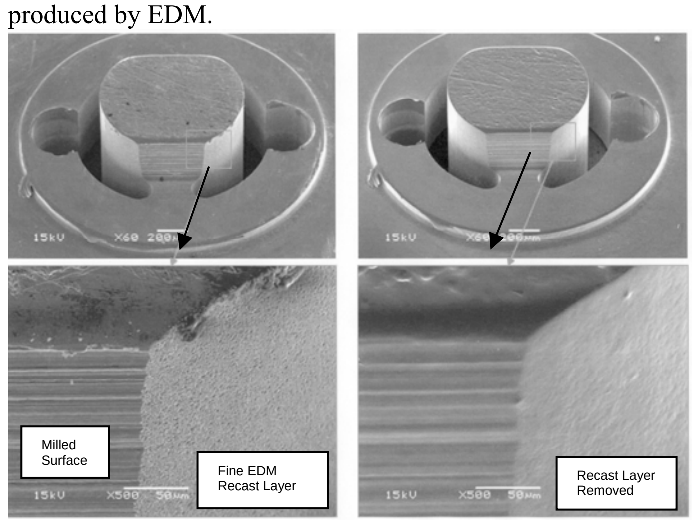

Figure 11 – EDM Recast Layer with Fine Roughness Removed from a Pivot Pin (0.94 mm diameter) using the Electropolishing Method

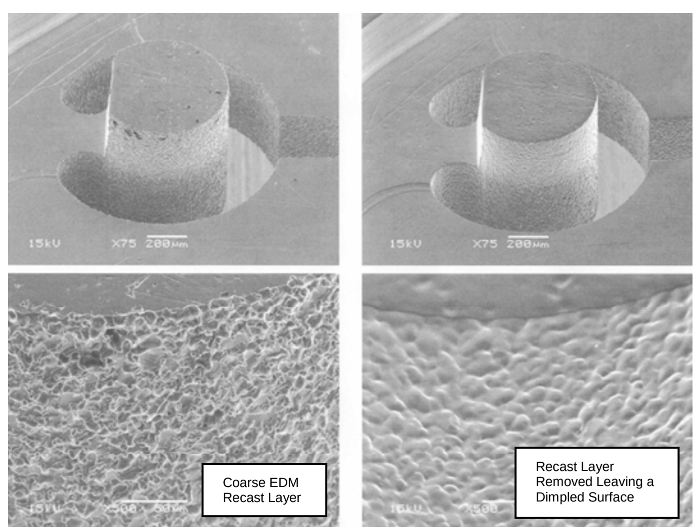

Figure 12 – EDM Recast Layer with Coarse Roughness Removed from a Registration Pin (0.78 mm diameter) using the Electropolishing Method

EXPERIMENTAL ELECTROPOLISHING PROCECDURE

Electropolishing is an electrochemical process with numerous variables including, but not limited to, solution composition and temperature, applied current (or voltage) and immersion time. Electropolishing solutions are material dependent and have been extensively studied for most metals. Other parameters, including current and immersion time, are usually determined empirically as they are more dependent on the metal's initial surface roughness and morphology than on metal composition. The applied current is particularly sensitive, more so than immersion time, because application of too low or too high a current will result in etching or pitting of the surface, respectively. The "polishing" current is therefore, an intermediate value which produces the smooth surface that is characteristic of electropolishing.

For this work, samples were electropolished using a HP 6200B DC power supply and Fluke 83 multimeter connected in series through the sample and counter electrode as illustrated in Figure 13. The applied current was controlled by the power supply and monitored via the multimeter.

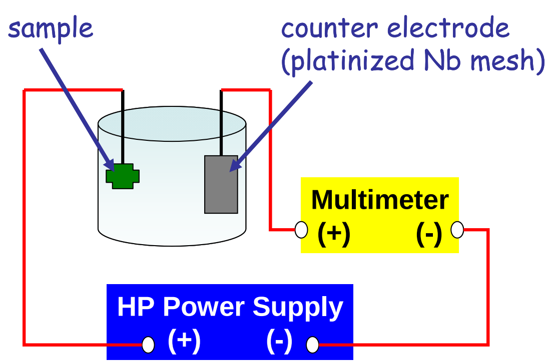

Figure 13– Schematic of Electropolishing Experimental Set-Up

The electrolyte selected for this project was 70% H_2SO_4 + 20% glycerin + 10% H_2O (volume %) at ambient temperature, based on the work of Wynick et al. [2]. In their work, the electropolishing current/voltage was determined by an automatic feature of their polishing equipment and was not reported; polishing times ranged from 10-30 seconds. In previous work, this electrolyte had been used to successfully electropolish Inconel 718. It was of interest to determine if it would be an appropriate electrolyte for other types of stainless steels.

ELECTROPOLISHING RESULTS

Electropolishing can be used to effectively remove the recast layer from EDM parts as shown in Figures 11 and 12.

In this study, two clock plates were supplied for electropolishing. Due to this small sample set, the goal of this work was limited to determining the limits for the applied current, at a constant immersion time of 2 minutes. Because of the relatively large size of the part (>5 cm^2 exposed area), the maximum applied current used was the maximum value allowed by the power supply (1940 mA). The maximum current density of 366 mA/cm^2 was used for 2 minutes. (The current density is defined as the applied current divided by the exposed surface area.) The recast layer was completely removed, however there was uniform "scalloping" of the surface. The resulting morphology indicates that the applied current used in this case was too high which resulted in excessive hydrogen evolution. The second sample was polished using a lower current density of 200 mA/cm^2. In this case, the applied current was not high enough to remove the recast layer and there is very little noticeable effect of electropolishing. The applicable range for the current density was determined to be between 366 and 200 mA/cm^2, for an immersion time of 2 minutes.

LOW-FRICTION HARD COATING FOR ELECTROPOLISHED BEARING SURFACECS

The friction and wear characteristics of the electropolished bearing surfaces were evaluated to determine the need for coatings. Figure 14 shows the typical friction behavior for an electropolished 21-6-9 SS EDM surface prior to the application of DLN coating. As soon as the native oxide is removed, the initial COF (~0.2) increases within the first few cycles of sliding. It should be noted that the COF at the end of the test reached around 0.7, with large fluctuation in the COF. Since this Tribological behavior is unacceptable for any robust mechanism interface, a thin (1.0 µm) DLN hard and low-friction coating was applied on the electropolished surface. A thin titanium layer was applied first to enhance adhesion and Diamond-Like Nanocomposite (DLN) coatings were applied by a plasma enhanced chemical vapor deposition technique from a siloxane precursor. The coatings were obtained from a commercial vendor, Bekeart Advanced Coatings Technologies. The fundamental mechanisms of friction in DLN coatings and its application to micro-scale mechanisms parts are described in our reports [4, 5].

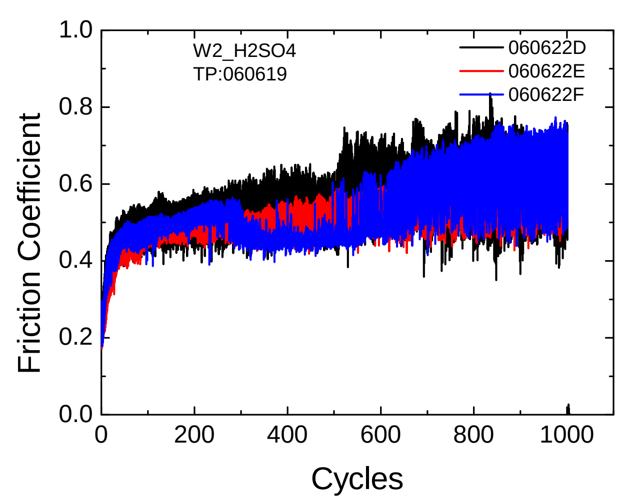

Figure 14 – Friction Behavior of Electropolished EDM Surface of 21-6-9 SS Alloy (i.e. No DLN Hard Coating)

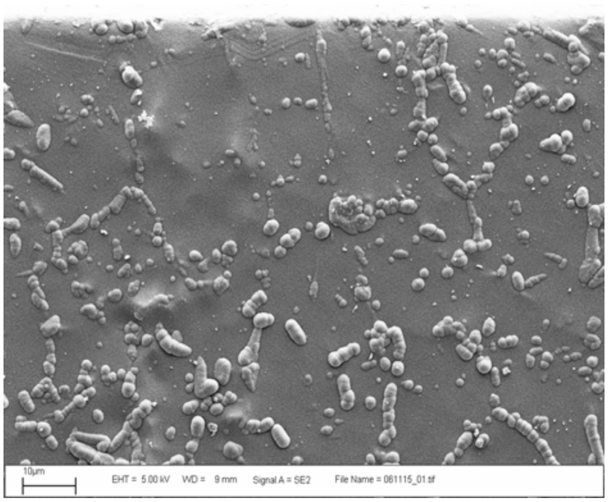

Figure 15 – Scanning Electron Micrograph of the DLN Coating on an Electropolished Surface of 21-6-9 SS Alloy

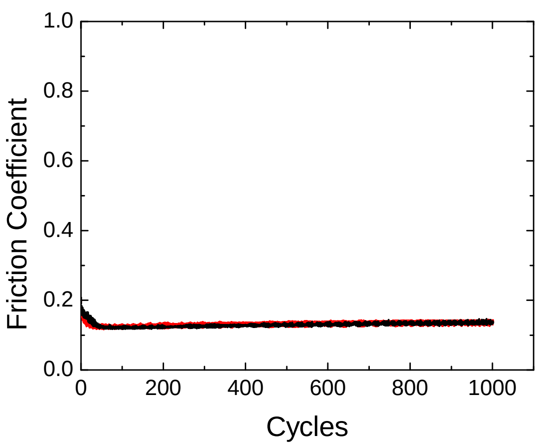

Figure 16 – Friction Behavior of DLN Coated Electropolished Surface of 21-6-9 SS Alloy

The DLN coated electropolished surface showed remarkable improvement in the tribological behavior, with COF of 0.15 throughout the 1000-cycle test cycle (see Figures 15 and 16).

PROPOSED FUTURE WORK

The EDM recast layer varies in terms of surface roughness and thickness depending on several processing parameters. Manufacturing parameters need to be further investigated to achieve consistent control for these characteristics and establish guidelines to produce a consistent and repeatable micro-wire EDM trimming process. An adequate number of EDM samples will be required to inspect for recast layer roughness and thickness variation to determine a repeatable tolerance for thickness.

The EDM recast layer contains stress concentration crevices that will significantly affect fatigue life and it therefore needs to be removed. The electropolishing results clearly show that it can effectively remove the recast layer from the EDM bearing surfaces of a clock plate, however appropriate polishing parameters have yet to be established. The EDM samples mentioned above will be required for electropolishing and inspection to define an electropolishing process with a known, repeatable tolerance for thickness of material removal.

The DLN hard coating applied to the electropolished bearing surfaces provides improved wear resistance with a consistent friction coefficient. DLN thickness tolerance on planar surfaces is about ± 10% of the thickness, but side-wall thickness tolerance is unknown. Because the pivot pin bearing surfaces are side-wall features, the electropolished EDM samples mentioned above will be required for DLN coating and inspection to define a repeatable DLN side-wall coating thickness tolerance.

Additional friction, wear, shock, and fatigue testing for a specific application's design life would be needed.

SUMMARY

A method for creating high-strength metal clock plates with the precision necessary for meso-scale mechanisms has been demonstrated. The prototyped clock plates met their dimensional tolerance specifications and show the practicality of establishing a repeatable, stable, and high-yield production process for meso-scale clock plates.

Statistical tolerances need to be established for the process variation of EDM recast layer thickness control, recast layer removal thickness control, and DLN side-wall coating application thickness control.

ACKNOWLEDGEMENTS

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