A FATIGUE STUDY OF ELECTRICAL DISCHARGE MACHINE (EDM) STRAIN-GAGE BALANCE MATERIALS

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ABSTRACT

Six component strain-gage balances developed at Langley Research Center are fabricated from a single piece of material with the help of the electrical discharge machine (EDM). Recent studies about the effects of the EDM on surface integrity and fatigue life have indicated that the EDM reduces the fatigue life of components fabricated by this method. Since the strain-gage balances at Langley are used extensively here and at other Centers, concern was raised with the possibility that the balances fatigue lives may be shortened by the use of the EDM. Therefore, a fatigue study of electrical discharge machine strain-gage balance materials was undertaken. The purpose of this fatigue study was to determine how much the EDM process affected the fatigue life of balance materials by comparing EDM and regular milling machine samples. Also, simulation of a typical balance stress configuration was devised for the fatigue testing in order to obtain results more closely related to balance situations. The fatigue testing of the EDM and regular milling machine specimens to date has indicated that the EDM technique does reduce the fatigue life of balance material 15-5PH steel, the first balance material tested. This conclusion was based on comparisons of the specimens fatigue lives with theoretical and manufacturer's data. Hence, the EDM surface effects are detrimental to the fatigue life of this balance material. The results obtained indicate that future research will involve more fatigue testing to obtain a wider range of results for application in the design and maintenance of strain-gage balances. This future fatigue testing will be performed by altering fatigue variables such as specimen size, stress level, radii, machining rate, surface treatment, and any other variables deemed important to understanding the effects of the EDM on balance materials.

INTRODUCTION

The development of strain-gage balances at Langley Research Center, before the late 1950's, began with multi-piece transducers. The balance measurement sections were fabricated separately and then fastened together using various techniques such as bolting, dowel pinning, and welding. Since connections were used in the balances, the accuracies that were achieved were limited due to such things as zero shifts which are a common problem with multi-piece measurement devices. These early balances were the state-of-the-art of the time and served their purpose very well. But, as time passed and as researchers began to demand more accurate measurements the search for new design and fabrication techniques was intensified. This search led to the incorporation of as newly developed fabrication technology, in the late 1950's, the electrical discharge machine. This new machining technique, which practically burns material away to any given shape, allowed the balances to be fabricated from a single piece of material. The elimination of the connections within the balances caused an immediate increase in accuracy due to the reduction of zero shifts. Therefore, since its incorporation into the balance fabrication process the EDM has been a vital part of the development of strain-gage balances at Langley.

During this time, since the involvement of the EDM, many six-component balances as well as other force measurement transducers have been designed, fabricated with the EDM, and utilized in wind tunnels and other facilities as needed without any indication that their fatigue lives had been sacrificed by the EDM. And until recently with the various studies being published about the effects of the EDM on fatigue life, this idea was never studied relative to balances at Langley. Consequently this study then is an attempt to understand the EDM's effects on fatigue pertaining to balances and to apply this information to existing and future balances as needed.

BACKGROUND

Strain-Gage Balances

Strain-gage balances are transducers used to measure the aerodynamic loads encountered by wind tunnel models during wind tunnel tests. Some of the characteristics of the balances developed at Langley are as follows. First, balances are fabricated from a single piece of material, made possible by the EDM. This single piece construction is one characteristic that is required in order to attain the high accuracies wind tunnel researchers need. Second, the strain-gage balances are designed to undergo high stresses during testing in order to achieve high outputs from the strain-gages which in turn produces high accuracy, again a requirement of the researchers. Third, the principle measuring element used in

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strain-gage balances is a "double cantilever beam" as shown in figure 1. This type of configuration allows for excellent directional measurement when it is strain-gaged in a wheatstone bridge arrangement, also as shown in figure 1. In addition, this beam configuration encounters stresses that are so called "double bending stresses" and therefore the fatigue testing will incorporate this stress in the design in order to obtain results more applicable to balances. And fourth, strain-gage balances come in many different sizes depending on their load specifications. However, the use of the EDM is needed in order to fabricate the balances because deep and narrow slots are incorporated into each of them regardless of their size.

Electrical Discharge Machine

As mentioned above the electrical discharge machine is used to perform the precision machining of the deep and narrow slots of each balance. The basic operation of the EDM is that it removes metal from a workpiece by an erosion process using an electric spark. In figure 2 a basic set-up of the EDM is shown with all of the main components listed. As illustrated, when a DC voltage is applied across the workpiece and the electrode, and the gap between the workpiece and the electrode is small enough to cause the dielectric fluid (the substance that the workpiece is submerged in) to ionize, a spark will jump across the gap from the electrode to the workpiece. This spark will release a large amount of energy and vaporize material from the workpiece in the vicinity of the electrode. This process takes place without the tool or the electrode coming in contact with the workpiece. The amount of material removed by the spark is determined by many factors such as the gap voltage, current, and others that are discussed in more detail in reference [4]. However, after the spark vaporizes the material the voltage across the electrode and workpiece goes to zero and the spark discharge to erode material away to a desired shape. The spark discharge releases a large amount of energy to vaporize the material away. During this energy release the surface of the material at the point of machining which is not vaporized, is actually melted. Then when the flushing and quenching take place this surface region resolidifies and is then recast back onto the workpiece. This surface layer is left with tensile residual stresses and microcracks along with a brittle characteristic. Also, the subsurface is heated to a temperature near its melting point and then cooled rapidly during the quenching process, leaving it with very hard brittle characteristics almost as if it were re-heat treated. As mentioned before these characteristics are detrimental to the fatigue life. Therefore, recent studies state that the inherent nature of the EDM is to leave a workpiece with material characteristics that reduce the fatigue life. These characteristics left by the EDM on a material are shown in figure 3 and discussed further in reference [1].

FATIGUE TEST SERIES DESIGN

The fatigue test series design was undertaken in order to perform the fatigue tests necessary to acquire information about the effects of the EDM on strain-gage balance materials fatigue lives. The comparison of the fatigue lives of regular milling machine specimens and EDM specimens was used as a basis for determining how much, or if the EDM changed the fatigue life characteristics of balance materials. The basic steps involved in designing the series were: determining the stress or strain, and specimen type; obtaining or designing a fatigue testing machine; and choosing instrumentation to monitor the predetermined parameters of interest.

The first parameters of the fatigue testing that needed to be determined were the stress or strain and failure type that would be utilized. The stress or strain type was defined to be completely reversed.
was determined to be complete fracture in order to determine the cyclic life difference, if any, between the two specimen samples. With the fracture type known only a few other factors were needed to determine the magnitude of the stress cycle. Therefore, the fatigue testing stress or strain level was set for finite life testing near the endurance limit, in order to obtain test data near the point of infinite life of the material, but to indicate if the EDM specimens lives varied greatly from the regular milling machine ones.

The specimen type was the next parameter chosen during the test series design. In figure 4 the specimen for the fatigue testing is shown. This type of configuration was chosen to simulate a typical measurement section in a strain-gage balance and obtain fatigue data as closely related to balances as possible. The general dimensions of the specimen were obtained by reviewing the sizes of existing balances and coming up with a representative sample. Exact dimensions were calculated in conjunction with the fatigue testing machine design in the next step of the design series. Grain direction or orientation of the specimen was again decided upon by the grain direction of a typical balance measurement section. Another parameter that was specified was the surface finish and this also is of an ordinary balance. Figures 4 and 5 display the specimen described here along with the machining parameters that were specified to machine the specimens to their given tolerances as dictated by normal balance machining practices. The heat-treatment for each material tested will vary with the machining parameters that were specified to machine the specimens to their given tolerances as dictated by normal balance machining practices. The heat-treatment for each material tested will again be the same as that used for balances. Figure 6 lists the various materials used for balances with their respective heat-treatments.

With all of the preliminary parameters defined the next step was to obtain or design a fatigue testing machine. Using these parameters to roughly estimate the load and frequency requirements of the machine, it was decided that a fatigue testing machine with these characteristics would not be easily obtainable. Therefore, the design of a fatigue testing machine was undertaken. Along with the approximate load and frequency requirements already mentioned some other features that were to be incorporated into the design were that the machine should have variable stress or strain testing levels, ease of specimen and machine maintenance, and that it be durable.

Figure 7 is a picture of the fatigue testing machine that was designed. The initial components that were designed were the input driving force and the deflection mechanism based on the approximate load and frequency requirements described earlier. The input driving force was specified as a 1/4 HP electric motor with approximately 9.5 in-lbs of torque capability while operating at 1725 rpm. The deflection mechanism was defined to be a "positive-return follower with constant diameter cam." This mechanism would allow the specimen to be deflected in the completely reversed bending cycle that was required. In addition, the connection of the deflection mechanism to the specimen was made possible by incorporating a moment arm between them as shown in figure 8. Also, by allowing the moment arm to be adjusted to different lengths the variable strain requirement would be satisfied.

With the above components defined, a deflection analysis was then performed on the entire system; specimen, moment arm, and deflection mechanism; to determine the final dimensions of these components. As shown in figure 9 the deflection analysis revealed that the constraints of the design were the strain level that must be attained for the testing and the torque limit of the motor. Therefore, an iteration process followed in order to size the specimen, moment arm, and deflection to attain the required strain level without over-torquing the electric motor. Results of this iteration process are shown in figure 9A.

A schematic and picture of the final fatigue testing machine are given in figures 7 and 8. The positions shown on the base and moment arm allow for different strain testing levels. During normal operation when the motor turns the cam and moves the drive bar to deflect the moment arm and specimen through the required strain level, the drive bar guides keep the apparatus aligned so that unwanted deflections are minimized. The cam has a needle bearing slipped over it in order to eliminate galling between the drive bar and the cam as well as to assure smooth operation of the machine. In addition, all areas of the machine are accessible for maintenance purposes and the machine has shown durability through the testing to date thus satisfying the initial design requirements.

Once the apparatus for performing the fatigue tests was designed, the next step was to decide on the instrumentation to use to acquire the needed data. The basis of the fatigue testing was to compare results between regular milling machine and EDM specimens by the use of stress versus log life (S-log N) curves. Therefore, to develop S-log N curves for the EDM and regular milling machine specimens the strain levels during testing and the number of cycles until failure needed to be monitored. The strain levels were monitored by the application of strain-gages (5K-12-050AFH-350), connected to external Wheatstone bridge completion units, at critical points on the specimens and recording their outputs. The cycle counting was achieved by placing a proximity probe near the end of the drive bar and connecting the probe to a digital counter to record the cycles. Also, by monitoring the strain-gage output using a computer and connecting various other devices through a computer to the electric motor, an automatic shut-off device was designed and incorporated in order to terminate testing after a specimen failed. Figure 10 gives a picture of the entire setup with instrumentation and figure 11 is a schematic of the automatic shut-off device with its operation explained.

EXPERIMENTAL RESULTS
The results of the fatigue testing to date are plotted on a graph of stress vs. log life (S vs. log N) in figure 12. Due to the nature of the testing, constant deflection, the stress was calculated from Hooke’s law in order to create the S vs. log N plot. This stress calculation was possible since the fatigue testing took place in the high cycle fatigue range, near the endurance limit of the material, and the dominant strain in this region of testing is the elastic strain. Therefore, Hooke’s law could be utilized to calculate the stress testing levels and create an S vs. log N plot.

As seen by the graph in figure 12 the regular milling machine (RMM) specimens were in quite good agreement with the theoretical curve, therefore this curve was used to compare the EDM specimens fatigue lives to and determine the fatigue life effects caused by the EDM. The theoretical or calculated curve was obtained using the following equation from reference 8:

\[ S_f = 10^a N^b \exp\left(\frac{0.85a}{S_e}\right) \]

Where,

\[ a = \log\left(\frac{0.85a}{S_e}\right) \]
\[ b = -\frac{1}{3}\log\left(\frac{0.85a}{S_e}\right) \]

S_f - fatigue strength
N - fatigue life
S_e - endurance limit of material (S_e = \frac{1}{2}S_u)

The EDM data points are plotted on the same graph as the theoretical curve and the regular milled data points. A least squares curve was fit to the data by assuming the data fit a curve similar to that used to develop the theoretical curve. The procedure for fitting the data, as done in reference 8, is explained: First, a linear log-log line of the form shown below was assumed to fit the data.

\[ \log(S) = b\log(N) + a \]

Second, the least squares method was used to determine b and a above. Third, the above equation was then transformed back into its final form as shown below with the values of b and a.

\[ S = N^b 10^a \]

Where,

\[ b = 5.70315 \]
\[ a = -1.4802 \]

The graph indicates that the EDM specimens fatigue lives are approximately 25% less than the regular milled specimens fatigue lives or the theoretical predicted lives, which clearly indicates that the fabrication of this material, 15-5PH steel, using the electrical discharge machine does reduce its fatigue life.

Once the EDM was shown to reduce the fatigue life of the material tested, the surface and subsurface effects left by the EDM was looked into. The first step involved viewing selected fracture surfaces of specimens using a scanning electron microscope (SEM). This process revealed that there were no distinct differences in the fracture surfaces of the regular milled specimens and the EDM specimens. This result indicated that the bulk of the EDM specimens material was the same as the regular milled ones and that the fatigue lives were different due to the EDM specimens initiating a crack earlier causing a shorter fatigue life. This further verifies that the surface of the EDM specimens have characteristics such as microcracks and tensile residual stresses which are catalysts for fatigue cracks.

The next step in studying the EDM surface effects was to do a microstructure study on some selected specimens. The results of this study were not available at this writing but will be included in the conference presentation. However, the purpose of this microstructure analysis will be discussed.

The main purpose of studying the microstructure of the EDM specimens is to determine the thickness of the layers, containing microcracks and other characteristics as discussed earlier and in reference [1], caused by the EDM. These surface and subsurface effects left by the EDM will be revealed by this study because of the microstructural differences that can be seen between a material with minimal defects and a material with microcracks and tensile residual stresses. The thickness of the EDM effects needs to be known to first assess the machining parameters used for these specimens. And second, the thickness needs to be known in order to determine the amount of material which would be treated by a post-treatment technique, such as shot peening that is discussed in the next section, to increase the specimens fatigue lives. Therefore, the results of the microstructure analysis are very important to the current fatigue testing results and future testing as well.

**FUTURE RESEARCH**

The fatigue testing results to date have clearly shown that the EDM is detrimental to the fatigue life of balance material 15-5PH steel. The goal of this study was to gain some knowledge about the EDM’s effects on strain-gage balance materials. Also, the goal was to be able to apply this knowledge to the maintenance of existing balances and also possibly incorporate it into the design of future balances. In order to obtain enough knowledge about the EDM’s effects on strain-gage balance materials to apply it, more testing will need to be performed on specimens which differ in any of the following categories from the original specimens but still have characteristics representative of existing balances. The categories are:

- beam sizes
- radii sizes
- machining rate
- material
- surface finish
- other

In addition to developing some fatigue life standards to go by when using balances or designing them when...
they are to be EDM'ed, methods under the other category may also help in understanding the EDM's effects on balance materials. These other methods that will be studied are surface treatment techniques which may help to improve the fatigue life of the EDM'ed balance materials. The goal in this area is to apply these techniques such as shot peening and electro-polishing, two of the most promising techniques as found through a literature search to date, to specimens similar to those already fatigue tested and observe any life differences if they occur. This part of the fatigue study will also, if the results dictate, be applied to existing and future balances to increase their fatigue lives as needed. The following two paragraphs will briefly discuss the basics of the two methods mentioned above, shot peening and electro-polishing.

Shot peening is a surface treatment technique that is similar to sand blasting but is much more controlled. Shot peening involves impinging shot, of a specified material and size, onto the surface of a material at a controlled rate to induce surface compressive residual stresses. As discussed earlier these types of stresses are known to increase fatigue life. Therefore, shot peening would relieve the tensile residual stresses induced by the EDM on a material and introduce compressive ones to prolong the fatigue life. However, this method is still being studied because the application of this technique to a strain-gage balance would be a difficult task due to the geometric complexity of deep and narrow slots which are almost inaccessible. Shot peening is described in more detail in reference [6].

Electro-polishing is another surface treatment technique for improving the fatigue life of a material. This process is sometimes called reversed plating because it removes material instead of adding it. Electro-polishing involves immersing a metal part and a cathode into an electrolyte. By electrically charging the metal part and applying a current, metal ions are removed from the part and drawn to the cathode at a controlled rate. This technique is said to leave no surface effects as the EDM does and would be used to remove the recast layer and possibly the heat-affected zone that is left by the EDM. Therefore, by removing the layers of the material which contain microcracks and tensile residual stresses the fatigue life of the material would be increased. The electro-polishing technique is discussed in more detail in reference [2].

In summary, much more fatigue testing is needed in order to gain enough knowledge about the EDM's effects on strain-gage balance materials to be able to apply these results to the maintenance and design of existing and future balances. However, the results of any testing that is done will be utilized as soon as it becomes available.

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ELECTRICAL DISCHARGE MACHINING

Figure 1

Figure 2

Figure 3

Figure 4

DOUBLE BENDING BEAM

Recent EDM study ( EDM Digest )

EDM'd surface
Recast layer
Heat affected zone
Parent metal

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**MACHINING PARAMETERS**

Specimen (c = 0.135 in.)

1. Rough beams to: .276 in. x .996 in. (outer dimensions)
   Rough slots to: .144 in. x .996 in. (inner dimensions)
   - On time: 85%
   - Off time: 15%
   - Cut rate: low frequency

2. Finish beams to: .270 in. x 1.000 in.
   Finish slots to: .150 in. x 1.000 in.
   - On time: 30-50%
   - Off time: 70-50%
   - Cut rate: high frequency

**Note:** Machine used for fatigue specimens was a Charmilles D10 with an Isopulse Type P25 power supply.

This routine of roughing the beams at a low frequency and finishing the beams at a high frequency is typical for all EDM work done for the force and strain instrumentation section at Langley. The routine is required in order to obtain the surface finishes and maintain the quality control standards set by the section.

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**SPECIMEN**

**Material:** 15-5PH Steel (from NASA stock)

**Composition:**
- Carbon: 0.07%
- Manganese: 1.00%
- Phosphorous: 0.04%
- Sulfur: 0.03%
- Silicon: 1.00%
- Chromium: 14.00-15.50%
- Nickel: 1.50-5.50%
- Copper: 2.50-4.50%
- Columbium plus Tantalum: 0.15-0.45%
- Iron: balance

**Heat Treatment:** To Condition H=915/935°F for 4 hours air cool (RC 40-42)

**Surface Finish:** 20 x 10⁻⁶ in. (20 micro inches)

**Note:** The composition of 15-5PH is similar to 17-4PH steel, another common strain-gage balance material.

**Other Balance Materials And Their Respective Heat Treatments**

**Material**

**Heat Treatment**

- **17-4PH Steel:** H925 (RC 40-42)
- 200 Grade Margining Steel: H900 (RC 41-45)
- 300 Grade Margining Steel: H900 (RC 52-55)

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**Figure 5**

**Figure 6**
DEFLECTION ANALYSIS

\[ \text{DEF} = \frac{F_i}{E_{21}} \times \frac{1}{L_{21}} \times \left( \frac{F_i}{E_{21}} \times \frac{1}{L_{21}} \right) + \frac{F_i}{E_{21}} \times \frac{1}{L_{21}} \]

\[ \text{STRESS} = \frac{F_i}{E_{21}} \times \frac{1}{L_{21}} \times \left( \frac{F_i}{E_{21}} \times \frac{1}{L_{21}} \right) + \frac{F_i}{E_{21}} \times \frac{1}{L_{21}} \]

- \( L_{21} \): Moment of Inertia
- \( E \): Modulus of Elasticity

\( i, j, k \) = # of double bending zones

Figure 9

DESIGN RESULTS

| SPECIFICATIONS | SPECIMEN | MOMENT ARM |
|----------------|----------|------------|
| SIZE           | 1 \times \text{15X.56 in.} | \text{N}, \text{25X1 in.} |
| M.A RANGE      | -----    | 5.05-6.65 in. |
| MATERIAL       | 15-5PH   | 15-5PH     |
| SURFACE FINISH | 20X10^-6 in. |-----|

CAM OFFSET OR DEF. = 0.69 in.
MAX. FORCE \( F = 15.3 \) lbs
MAX. TORQUE AT MOTOR = 9 in.-lbs

Figure 9A

FATIGUE TESTING MACHINE

Figure 8

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TEST SET-UP

Figure 10
A fatigue test begins with the #1 switch of the solenoid completed and the power supply for the electric motor in line with the variac. Once the test has begun the computer monitors the peak to peak voltage of a strain-gage on a specimen via the voltmeter. When a specimen fatigues one of its beams will fracture. Therefore, the tension side of the stress cycle for the fractured beam will cause the fracture to open and less strain to be applied to the specimen resulting in an output voltage drop. Hence, if the voltage output of a strain-gage goes below a predetermined limit programmed into the computer, signaling a specimen has failed, the computer will signal the relay actuator to complete the circuit between a power supply and switch #2 of the solenoid. Switch #2 of the solenoid is now the completed circuit which automatically disconnects switch #1 and the power to the electric motor which shuts it off.

**Figure 11**

**FATIGUE TESTING RESULTS**

Stress vs. Log Life, S-Log(N) Diagram

**Figure 12**