MAXIMIZING THE FATIGUE STRENGTH OF A CARBURIZED HELICAL GEAR VIA OPTIMIZING SHOT PEENING PROCESS PARAMETERS – PART 1: ALMEN INTENSITY

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ABSTRACT

Historically, shot peening has demonstrated the potential for substantial increases in fatigue strength. The lack of consistency in reproducing these values in production can be traced to inadequate testwork data behind the process specification and inadequate production process control.

The authors present the type of testwork necessary to produce a process specification wherein the optimum parameter nominal values and production tolerances necessary to obtain a minimum fatigue strength value are defined. The use of microprocessor controlled shot peening equipment to produce specimen conditions representing strategically selected parameter values, and the fatigue testing modes of constant amplitude followed by dynamometer validation are necessary. Depending upon the workpiece characteristics and its workload environment, over a half dozen process parameter nominal values and acceptable tolerances as well as numerous sub-parameters must be defined.

This paper will describe Part 1 of the testwork, which is to identify the optimum nominal value of the process parameter called almen intensity.

INTRODUCTION

The opportunity exists for significant increases in fatigue life through shot peening. Optimizing the benefits of the process, and safely incorporating the benefits into the design of the component, enabling increasing the design rating, weight removal, or utilization of a less expensive material, requires the following:

A) Discovery:

1. Identification of all shot peening related variables and process parameters that can affect workpiece fatigue life.
2. Establishment of optimum levels and tolerances of each variable.

B) Control:

Consistently controlling and monitoring the optimum levels of each variable within the required tolerances in production volumes and shop environments.

Another way of stating it, the challenge is one of:

1) Predictability

2) Reproducibility

3) Verifiability

There currently exists no known way to nondestructively verify the correctness of the shot peening process. One critical step toward achieving verification is the close monitoring and recording of critical process parameters and comparing these with optimization testwork data and tolerances. The goal of the testwork performed under this project is to develop the optimization testwork data and tolerances for a Chrysler transmission output gear.

The result will be a process specification providing for the incorporation of the optimized shot peening results into the design fatigue strength. The resultant higher strength/weight properties present options to the engineer such as reducing weight, increasing the stress capacity or substitution of a less expensive material.

The successful completion of a two phase test program requires:

1. Establishment of almen intensity and saturation optimum nominal values and the corresponding fatigue strength.

2. Establishment of production tolerances involving the remaining process parameters and sub-parameters necessary to accomplish the above objective.

Although shot peening parameter optimization studies have previously been performed, very little, if any have involved the precise process control procedures and the single tooth fatigue testing utilized in this project on a carburized helical gear.

BACKGROUND

The process parameters are optimized in decreasing order of their relative influence on fatigue strength. In most cases, once workpiece saturation has exceeded 100%, almen intensity is the most dominant process parameter and therefore is optimized first.

Almen intensity is an indirect method of monitoring the aggregate amount of energy transfer or residual compressive stresses imparted to the workpiece, the method employs the use of a strip of 1070 spring steel, 44 Rc-50 Rc, as illustrated in Figure 1. For this study almen A strips were used up to an intensity of 0.024A". Thereafter, the thicker C strip was used.

TEST STRIP "A"

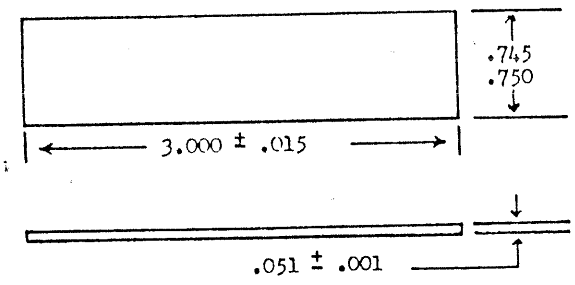


Figure 1

The strip is mounted to an almen block, as shown in Figure 2, and exposed to the blast in identical fashion as the critical area of the workpiece, with the same process parameters.

HOLDING FIXTURE WITH TEST STRIP

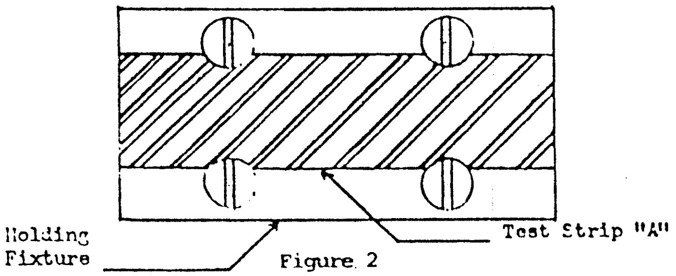
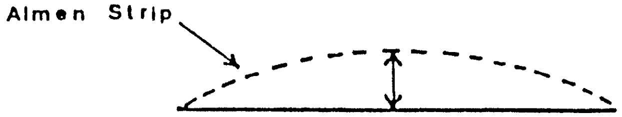


Figure 2

After peening, the almen strip is removed from the block and the amount of bow is measured by an almen gage. This measurement is called arc height. (See Figure 3.)

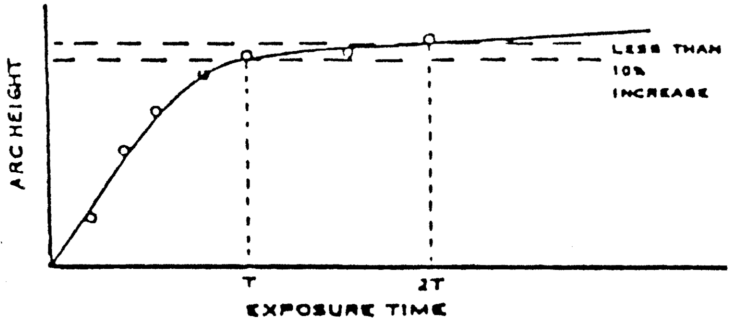


Measurement of Arc Height

Figure 3

Almen intensity is arc height at saturation. It is quantitatively developed by plotting arc height vs. exposure time to the blast. Almen saturation is defined as the minimum arc height where doubling the exposure time to the blast results in less than a 10% increase in arc height, as illustrated in Figure 4.

MIL-S-13165C



Saturation Curve Quantifies Almen Saturation

Figure 4

Initial parameter selection reflected past Phase I and Phase II research performd by Advanced for the U.S. Air Force Wright Aeronautical Labs, and experience with case hardened steels 1). This research indicates that optimum fatigue life through shot peening is a balance between the benefits of peening induced residual compressive stresses, which is dependent upon their magnitude and distribution, and peening induced surface damage. In the case of almen intensity, there is a relationship to the forming of laps on the surface or Peened Surface Extrusion Folds (PSEF). The higher the intensity, in relation to the workpiece hardness, the more frequent and deeper PSEF produced. In the case of workpiece saturation, the work hardenability and hardness of the workpiece and/or media material influences the point at which additional cold working or exposure time to blast, will result in micro-cracks or strain cracking of the surface.

Although the effect of the micro-cracks and PSEF is mitigated somewhat by the fact that they are macroscopically encapsulated in residual compressive stresses, their formation still has a negative influence upon fatigue strength when maximizing fatigue strength is the goal. As they increase in size and frequency that influence can become pronounced.

Thus, when increasing values of almen intensity are plotted against fatigue life a curve is developed where fatigue life increases to a point, and then declines with further increases in almen intensity. Identifying this peak is the purpose for the Part I testwork.

The fatigue life data is developed by A vs. B constant amplitude fatigue testing of individual gear teeth.

The fatigue testing is designed to:

1. Simulate the type and distribution of stresses, not necessarily the magnitude, produced in the root fillet area during operation.
2. Provide a fatigue test condition that is invariant from specimen to specimen allowing the comparison, in terms of resultant fatigue life, of incremental changes of strategically targeted process parameters, essentially A/B comparison testing.

The purpose of the fatigue testing was not to perform validation testwork or to simulate actual operational conditions. Once the optimum parameter values have been determined, then validation testwork simulating actual operational conditions should be performed on gears peened to the optimum process parameters.

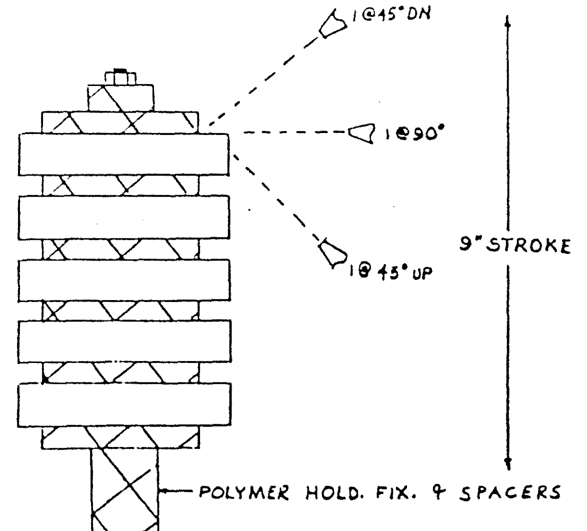
PROCEDURES

1. The gear material is AISI/SAE 4023 steel. The gear was carburized at 925 C (1700 F) and oil quenched such that the case depth to the hardness of 50 RC is in the range of 0.75 - 1.15 mm (0.030 - 0.045 inches). The gear was then tempered at 200 C (400 F) so as to maintain the surface hardness of 58 RC minimum.

The shot peening machine used was equipped with a microprocessor. The process parameter nominal values and tolerances were programmed into the microprocessor. In the event of a process parameter value exceeding the set tolerance the microprocessor would alarm, shut the peening machine down, indicate which parameter was at fault and retain in memory the necessary information to continue the peening cycle from the process interrupt point once the fault was corrected.

There were no alarms during the precision peening of the test specimens.

The gears were stacked on a rotating spindle with spacers to allow access to the fatigue critical areas. Three 3/16" diameter direct pressure venturi nozzles mounted in nonadjustable fixtures stroked the rotating stack (see Figure 5).



Schematic of Gear Specimen Peening Arrangement

Figure 5

The initial parameters of 0.018A" and 0.024A" at 110% workpiece saturation were chosen in the search for optimum almen intensity values.

100% workpiece saturation was originally estimated to be 175% to 180% of almen saturation based upon mathematical relationships derived from past research. Prior to peening, the tooth flanks and roots were coated with a flourescent tracer dye. The gear was then peened to almen saturation and examined under a black light and then under a binocular microscope at 20X power. The dye was still present and the peened surface was estimated to be 60% covered.

The gear was then peened an additional lot of time equal to 50% of the time that was required to reach almen saturation and re-examined. There was no evidence of dye on the surface, however, the coverage based upon examination of the impingement impressions was estimated to be only 90%.

An additional exposure time of 50% almen saturation time resulted in 100% coverage and 110% workpiece saturation based upon our original calculation. Therefore all of the gears for the almen intensity study were peened to 110% workpiece saturation by exposing them to the blast for double the amount of time required to reach 100% almen saturation.

All other parameters were held constant, within the tolerances shown in Table I, increasing only air pressure (shot velocity) to increase almen intensity and increasing shot size from S-230 to S-280 at an almen intensity of 0.08C".

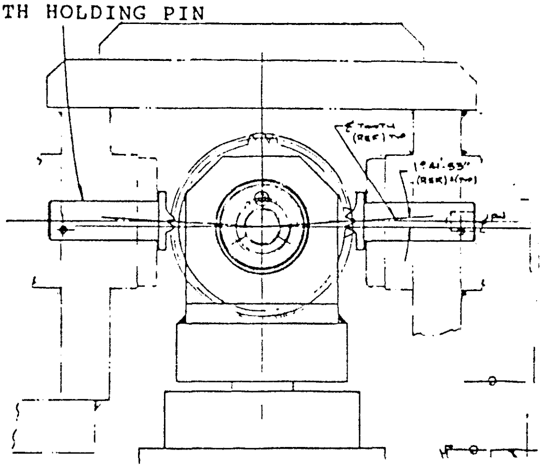
Table I

Peening Process Parameter Values and/or Tolerances

Process Parameter	Nominal Value and/or Tolerance
Shot Flow Rate	+/- 2 oz/min
Workpiece Saturation	110% = 200% almen saturation +/- 10%
Lance Speed	9 inches/min. +/- 1 inch/min.
Lance Stroke Length	9 inches +/- 5%
Specimen Rotation	30 rpm +/- 1 rpm
Angle of Impact	90 degrees +/- 2%
Air Pressure	+/- 1 psi
Shot Size and Shape	Exceeds MIL-S-13165-B Table I
Shot Hardness	54 Rc - 60 Rc
Almen Strip Flatness	+/- 0.0005 inch
Almen Strip Hardness	45 Rc +/- 1 Rc

2. Since the test program was directed towards increasing the strength of the root fillet area, the fatigue test mode chosen was high cycle cantilever bending of a single tooth at a time. The fatigue test machine utilized was a Sonntag SF-10 rotating mass type with an applied load capability of 10,000 lbs and an accuracy of +/- 2% from the set load. The applied load was monitored via a load cell placed between the load platform and the gear arbor fixture.

The fatigue test fixture is shown in Figure 6. The structure was manufactured out of cold rolled steel. The arbor was carburized and hardened. Each test gear was mounted on the arbor with its own set of bearings and was free to rotate. The test tooth and opposing tooth holding pins were manufactured from A-2 steel disks.



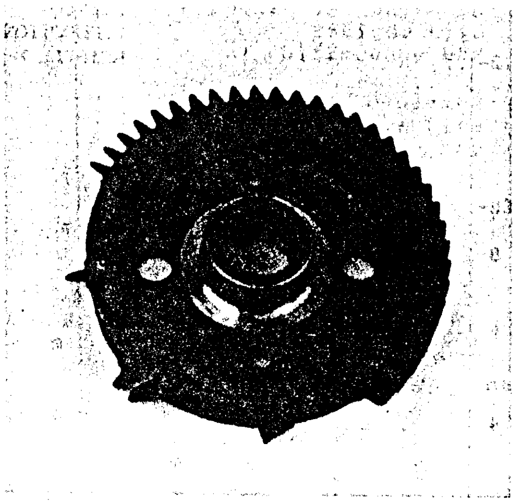
Output Gear Fatigue Test Fixture

Figure 6

The involute of the mating transfer gear was ground around the periphery of the disk. Pie shaped wedges were cut, from which the gear tooth holder pin was machined. The pins where then thru-hardened to 60 Rc.

The gear holder pins were free to rotate in needle bearings and were adjustable horizonally for tooth engagement.

Each test gear had two test teeth located 90 degrees from the other. One of the two teeth was masked during peening to provide a corresponding unpeened baseline value. Neighboring teeth were ground away after peening to avoid damaging the gear holder pins when tooth failure occurred. (See Figure 7.)



Output Gear with Two Isolated Test Teeth A & B
90 Degrees Apart

Figure 7

The ID of the test gear was mounted on the arbor and was free to rotate on its bearings. The test tooth was held in position via the holder pin while the opposing four teeth were positioned in the opposite holder pin to assure failure in the test tooth.

Because the tooth width of the holder pin was wider than the test tooth, allowing the pin freedom to rotate assured an even load across the test tooth pitch line. The cantilever bending of the test tooth was accomplished via oscillation of the arbor holder relative to the tooth holder pins. The stress ratio R was 0.1 and A was 0.818. Thus the test tooth bottom radius was subjected to only fluctuating tensile stresses. In an attempt to keep the tooth engagement line constant from gear to gear the holder pins were adjusted into the test gear pitch circle as far as they would go.

RESULTS

Figure 8 shows the data produced during the fatigue life versus almen intensity study. Figure 9 illustrates the same data plot comparing additional fatigue data produced from the same gear peened in a conventional high production fashion to a 0.024A" almen intensity. Although the almen intensity achieved was identical the sub-parameter values, such as impact angle, shot size uniformity and broken particle content, as well as the level of workpiece saturation were different. These gears were fatigue tested on the same machine and fixture as the precision peened data. Table 2 tabulates mean and Weilbull B-10 life from Figure 9.

The two parameter Weibull with 90% reliability was calculated by using a computer program developed by the NASA Lewis Research Center. The plotted Weibull values are the result of an iterative process starting with the entire population of data. The highest data value in the population is then removed and the resultant B-10 value compared with the first. As long as the B-10 value continues to increase the corresponding highest data value is removed from the population and a new B-10 life is calculated. Once the B-10 life decreases in value from the one previously calculated, that previous or highest B-10 value is used in the data plot.

DISCUSSION

The fatigue life scatter is broader than normally experienced for this type of testwork. Unpeened baseline exhibits the broadest scatter with the mean relatively high in comparison to shot peened mean life values. This is due, in part, to LCF (low cycle fatigue) testing instead of HCF (high cycle fatigue).

The test stress for HCF was too low for the crack to propogate to complete failure. A LCF mode was necessary. Testing in a LCF mode suppresses the influence that different process parameter values have upon fatigue life. The reason for this is illustrated in Figure 10.

Table 2

MEAN AND B-10 LIFE CYCLES TO FAILURE OF VARIOUS SPECIMEN GROUPS

	BASELINE	12A	18A	24A	8C	24A CONVENTIONAL PEENED
MEAN	9,850	16,571	23,800	33,167	24,750	16,375
B-10	56	7,708	11,512	11,953	3,568	2,663

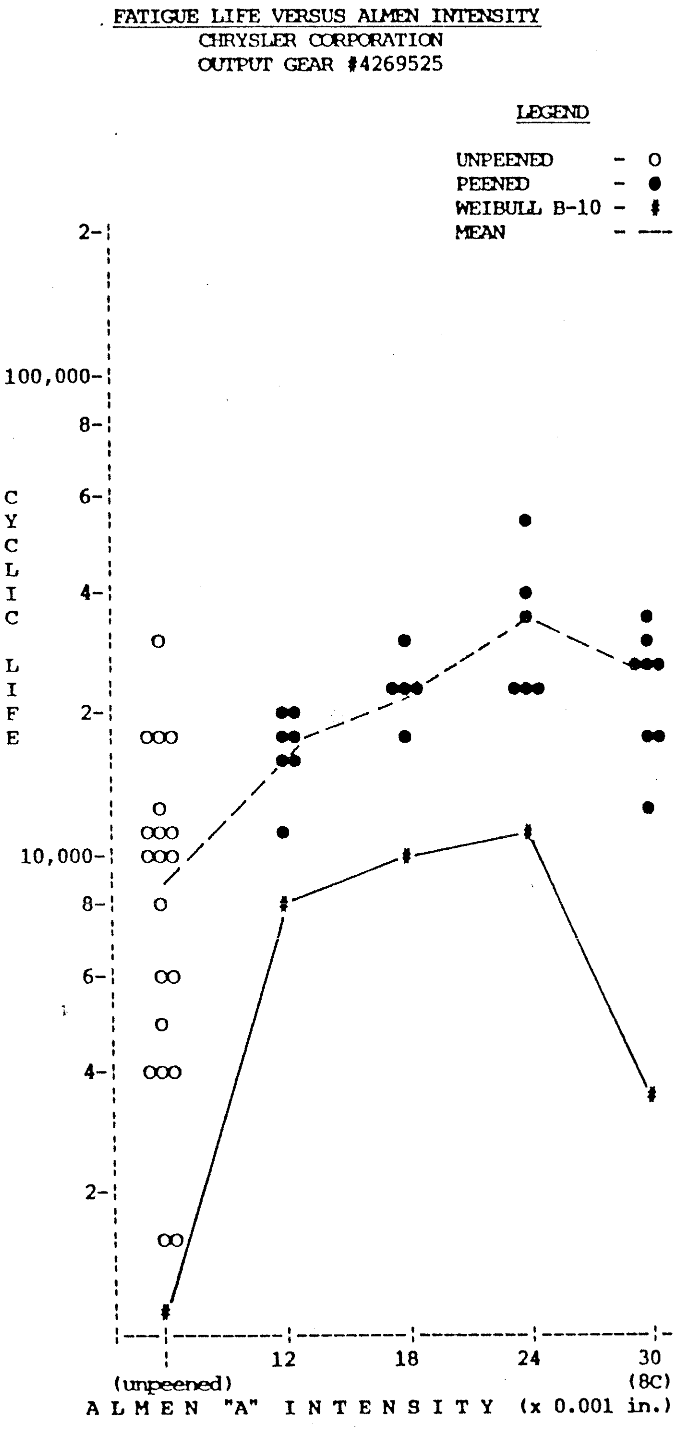


Figure 8

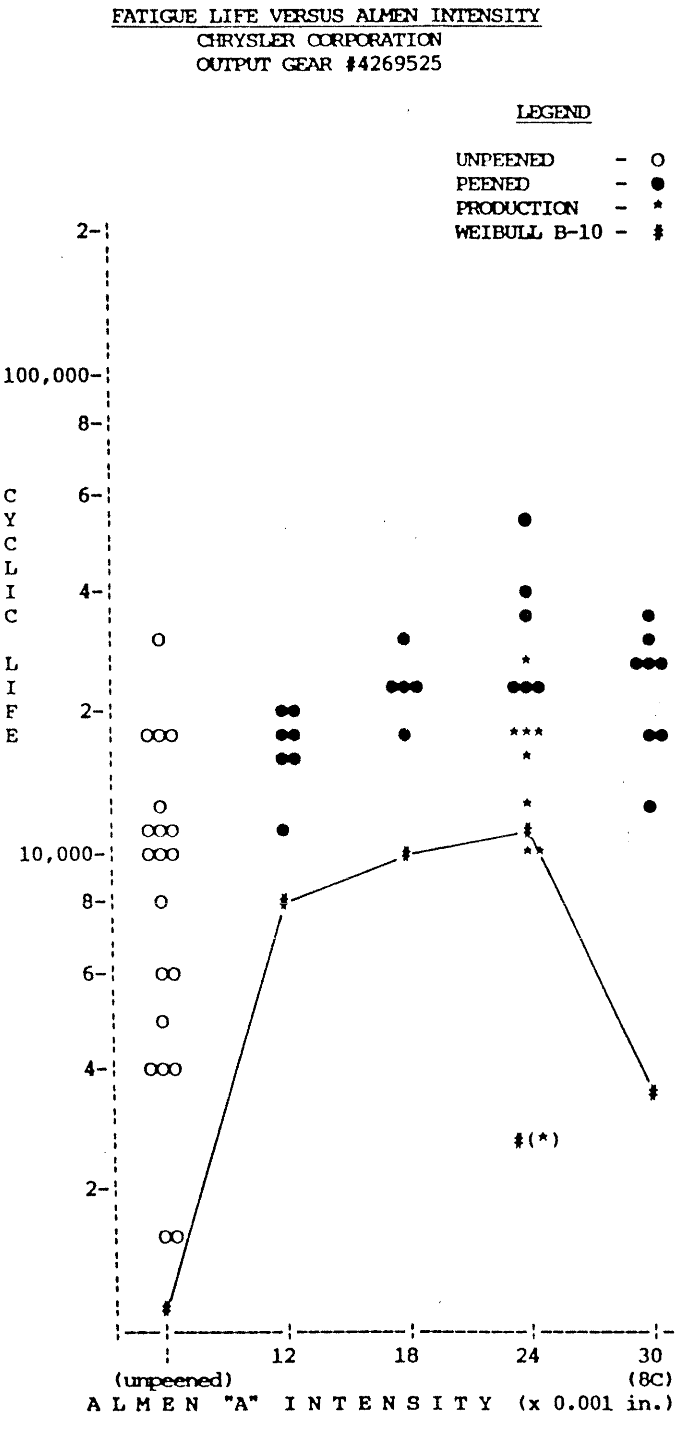


Figure 9

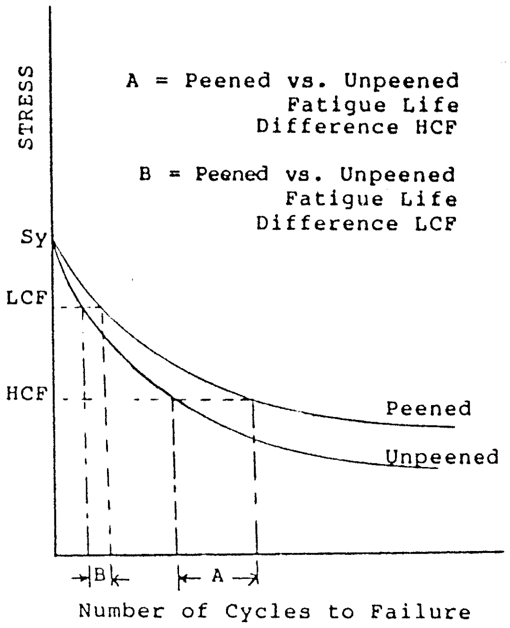


Figure 10

The S/N curve of a peened and unpeened workpiece merge at the yield strength, Sy, of the material. Therefore, as the mean test stress approaches yield the differentiation between peened and unpeened fatigue life is reduced. This, naturally, reduces the detectable influence that changes in almen intensity or saturation will have on fatigue life.

The result is fatigue life versus almen intensity and fatigue life versus saturation curves that lack the very pronounced peak or optimum that would be present for HCF testing.

All testwork performed to date at Advanced Material Process Corporation has produced results of increasing mean and/or B-10 fatigue life as almen intensity is increased until optimum fatigue life is obtained. Further increases in almen intensity result in decreases in fatigue life. The data illustrated in Figure 8 does follow this pattern.

This data plot indicates that the optimum almen intensity occurs between 0.018A" and 0.008C". Both the mean life and the Weibull B-10 life concur.

CONCLUSION

A. The optimum almen intensity is close to 0.024A" with S-230 steel shot 54 Rc to 60 Rc hardness (see Figure 8).

B. The increase in mean life unpeened compared to optimum peened was 237% at a very high test stress (see Table 2).

C. The increase in mean life of the Advanced peened 0.024A" intensity group compared to the conventional production peened 0.024A" intensity group was 100% and the increase in B-10 life was almost 350% (see Table 2).

D. The data pattern illustrated in Figure 8 is in agreement with data patterns developed in past testwork and supports the original premise that over peening is very possible due to the fact that optimum fatigue strength is a balance between the peening induced residual compressive stresses and peening induced surface damage.

References

1) Simpson, R. S. and Chiasson, G. L., 1988, "Quantification of the Effects of Various Levels of Several Critical Shot Peen Process Variables on Workpiece Surface Integrity and the Resultant Effect on Workpiece Fatigue Life Behavior" Technical Report AFWAL-TR-88-3029, Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio.