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IMPROVED FATIGUE LIFE OF A CARBURIZED GEAR BY SHOT PEENING PARAMETER OPTIMIZATION

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Abstract

The effect of shot peening process parameters on fatigue life was investigated on a carburized helical gear. In most of the shot peening parameter optimization cases, once workpiece saturation has exceeded 100%, Almen intensity is the most dominant process parameter and, therefore, is optimized first. Gear tooth bending fatigue lives were evaluated as a function of Almen intensity. Bending fatigue resistance of a carburized gear, shot peened via optimizing Almen intensity, depends on the magnitude and distribution of peening induced compressive residual stresses below the surface and a balance between the benefits of residual stresses and surface damage.

TOOTH BENDING FATIGUE is the most common mode of fatigue failure in gearing. Fatigue crack initiation occurs at the surface of the root radius of the tooth where the maximum bending stress is applied. It is well known that shot peening has demonstrated the potential for improvement in fatigue life of gears by introducing residual compressive stresses at and below the surface to retard fatigue crack initiation particularly in the high cycle regime. An extensive review of the improved fatigue performance of gears through shot peening is available in Ref. 1.

Optimizing the benefits of the shot peening process requires the identification of critical process parameters and the establishment of optimum levels and tolerances for each parameter. Among many process parameters are shot peening intensity(known as Almen intensity), workpiece saturation, shot size, shot hardness, impact angle, and broken particle content. These parameters are optimized in decreasing order of their influence on fatigue strength. In most cases, once workpiece saturation has exceeded 100%, Almen intensity is the most dominant process parameter, and is optimized first. The objective of this paper is to describe optimum nominal value of the Almen intensity for a carburized helical gear by evaluating tooth bending fatigue life, residual stress, and surface damage induced by shot peening.

BACKGROUND

ALMEN INTENSITY - 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 AISI 1070 spring steel in the 44-50 HRC hardness range. The strip is mounted to an Almen test block and exposed to the blast in identical fashion as the critical area of the workpiece, with the same parameters. After peening, the Almen strip is removed from the block and the amount of maximum deviation from flat is measured by an Almen gage. This measurement is called arc height. Details of the design and use of Almen gages and test strips are given elsewhere[2].

Almen intensity is arc height at saturation. It is quantitatively developed by plotting arc height versus 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 shown in Figure 1.

PREVIOUS STUDIES - Simpson and Chiasson[3] studied the effect of Almen intensity on fatigue life in Ti alloys, Al alloys and AISI 4340 steel hardened to 48-50 HRC. Optimum fatigue life through shot peening is a balance between the benefits of peening induced residual compressive stresses, which is dependent on their magnitude and distribution, and peening induced surface damage. There is a relationship between Almen intensity and the forming of surface laps or peened surface

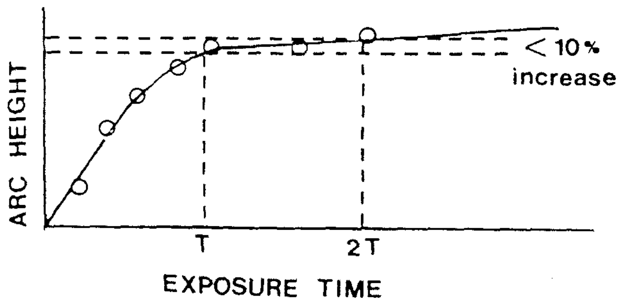

Figure 1. Determination of Almen saturation

Table I. Chemical Composition of the Test Gear

Element	Composition, %
C	0.20-0.25
Mn	0.70-0.90
P	0.035 max
S	0.040 max
Si	0.15-0.35
Mo	0.20-0.30

extrusion folds(PSEF). The higher the intensity, in relation to the workpiece hardness, the more frequent and deeper PSEF produced. Primary crack initiation was related to the presence of PSEF[3, 4]. In the case of workpiece saturation, the degree of work hardening and hardness of workpiece and/or media material affect the amount of cold working and exposure time for optimum fatigue life beyond which microcracks or strain cracking will result[3, 5]. Although the effect of microcracks and PSEF is reduced somewhat by residual compressive stresses, their formation still has a negative influence on fatigue life. As they increase in size and frequency, the effect becomes pronounced.

Hirsch et al[6] recently investigated the effects of shot peening on the fatigue behavior of case hardened gears made of 16MnCr5(German specification equivalent to AISI 5120). It indicated that improvements in fatigue behavior after different shot peening processes correspond with the magnitudes and distributions of residual stresses at or below surface. However, the effect of peening induced surface damage on the fatigue behavior was not studied.

TEST PROCEDURES

TEST GEARS - The test gear material is AISI/SAE 4023 steel from the same heat of lot. The nominal composition of the steel is given in Table I. The gears were carburized at 925°C (1700°F) and oil quenched so that the case depth to hardness of 50 HRC is in the range of 0.75-1.15 mm (0.030-0.045 inches). The gears were then tempered at 200°C (400°F) to maintain the surface hardness of 58 HRC minimum. The case microstructure consists of martensite with approximately 20% retained austenite along the surface, while the microstructure of the core is tempered martensite, as shown in Figure 2.

Each test gear had two test teeth located 90 degrees from the other, as shown in Figure 3. One of the two teeth was masked during peening(see below) to provide a corresponding unpeened baseline value. Neighboring teeth were ground away after peening to avoid damaging the gear tooth holding pins(shown in Figure 4) when tooth failure occurred.

SHOT PEENING PROCESS - shot peening was performed using a machine equipped with a microprocessor so that the machine is automatically shut down if the process parameters exceed the nominal values and tolerances programmed into the microprocessor. The gears were peened to 110% workpiece saturation for double the time required to reach 100% Almen saturation. Details of the procedures for workpiece saturation determination are described in Ref. 5. The gears were then peened to three Almen intensity "A" levels(0.012, 0.018, and 0.024 inches) using shot in the size of S-230, and to one Almen intensity "C" level of 0.008 inches with S-280 shot. All other parameters were held constant within the tolerances given in Table II, except for the air pressure(shot velocity) which was increased when the intensity increased.

FATIGUE TEST - Single tooth bending fatigue tests were conducted utilizing a rotating mass type of test machine(Sonntag Model SF-10) with 10,000 lbs loading capability. The test fixture is shown in Figure 4. The load with an amplitude of 2,500 lbs followed a sinusoidal waveform with a mean load of 3,200 lbs in tension-tension(R = 0.12) at 30 Hz.

RESIDUAL STRESS MEASUREMENT AND SCANNING ELECTRON MICROSCOPY - X-ray diffraction residual stresses were determined using a two-angle sine-squared-psi technique. Measurements were made at the surface and as a function of depth in the root-to-crown (radial) direction just above the root fillet radius of a tooth. From all interference

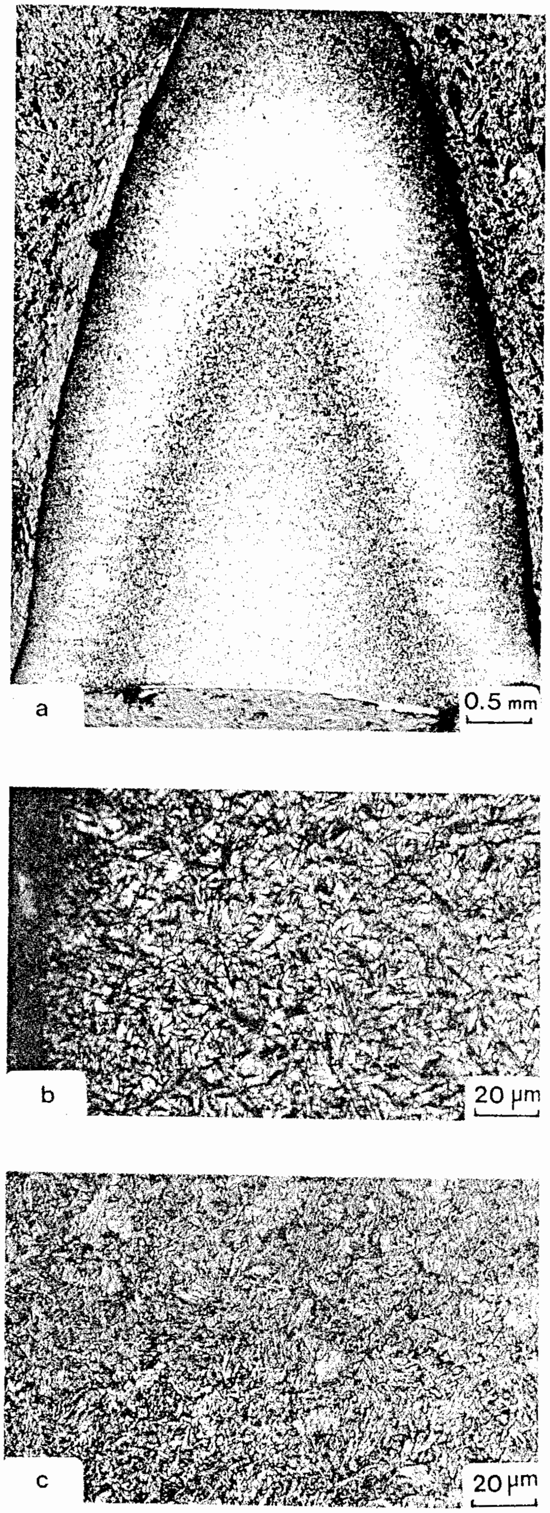

Figure 2. Microstructure of (a) test gear tooth (b) tooth case (c) tooth core

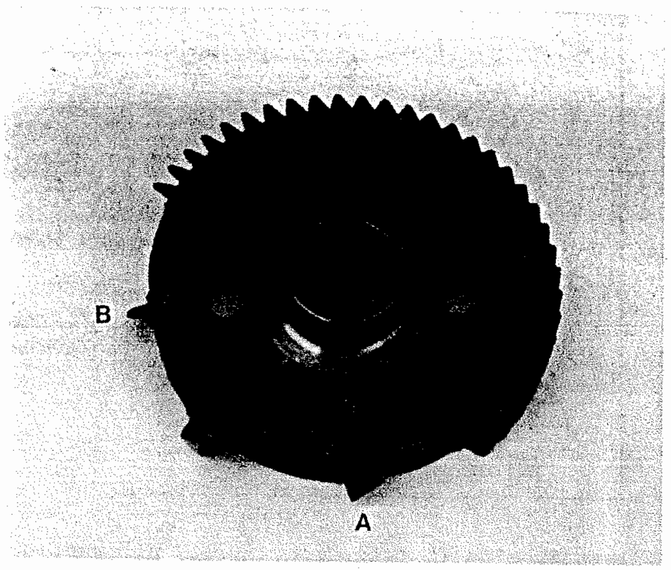

Figure 3. Gear specimen with two test teeth (A and B)

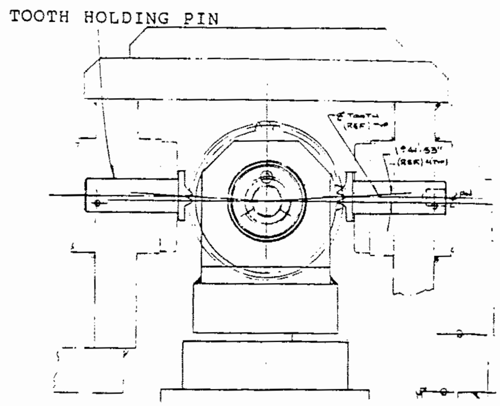

Figure 4. Fatigue test fixture

Table II. Shot Peening Process Parameters

Parameter	Nominal Value
Shot Flow Rate	± 2 oz/min
Workpiece Saturation	110%(200% Almen Saturation) ± 10%
Lance Speed	9 in/min ± 1 in/min
Lance Stroke Length	9 in ± 5%
Specimen Rotation	30 rpm ± 1 rpm
Angle of Impact	90° ± 2%
Air Pressure	± 1 psi
Shot Size and Shape	Exceeds MIL-S-13165-B Table 1
Shot Hardness	54-60 HRC
Almen Strip Flatness	± 0.0005 in
Almen Strip Hardness	45 HRC ± 1 HRC

lines, the half width, i.e., (211) diffraction peak width at half maximum was calculated simultaneously with the residual stress from the peak width. A scanning electron microscope(SEM) was used to observe surface topography changes and damage due to shot peening.

RESULTS AND DISCUSSION

Figure 5 shows the data obtained from the fatigue life versus Almen intensity study. The mean fatigue life was determined using the data excluding the high production gears conventionally peened to 24A Almen intensity at Chrysler Kokomo transmission plant. Although the Almen intensity for the production gears was identical to that for precision peened gears, the sub-parameter values such as impact angle, shot size uniformity, broken particle content, and workpiece saturation level are different. These production gears were fatigue tested on the same test machine and fixture as the optimum peened gears. The two-parameter Weibull B-10 life is also plotted in Figure 5. Table III tabulates mean and B-10 life for each specimen group from Figure 5.

The fatigue life scatter is broader than normally experienced for this type of testwork. Unpeened gears exhibit the broadest scatter in fatigue life with the mean life relatively high in comparison to shot peened mean life values. This is due, in part, to our choice of a low cycle fatigue(LCF) test instead of a high cycle fatigue(HCF) test. A LCF was necessary because the test load for HCF was too low for the crack to propagate to complete failure. Since the life spent in crack propagation dominates the fatigue life in a LCF test, it is difficult to detect any influence that the changes in Almen intensity or saturation will have on crack initiation and/or fatigue life. Therefore, the fatigue life versus Almen intensity curve in this study lacks the very pronounced peak or optimum value when compared with the HCF test results in the previous study[3]. This study indicates, however, that the optimum Almen intensity occurs between 18A and 8C for both the mean and Weibull B-10 lives. It also indicates that the optimum peened gears have better fatigue life when compared with conventionally peened production gears.

Figure 6 shows residual stress and half width distributions of unpeened and peened gears. The residual stress distributions of peened gears show typical maximum compressive stresses below the surface and a continuous increase to the values resulting from the carburizing heat treatment. Up to a nominal depth of 0.004 inches, the compressive residual stress for specimen 24A is higher than those for specimens 12A and 8C. Improved fatigue life for 24A specimens appears to be attributed to the higher compressive stress.

The area surrounded by the stress distribution curve and x-axis represents the energy transfer imparted to the workpiece by shot peening. The magnitude of the area increases with Almen intensity level. Although the energy for specimen 8C is greater than the other two specimens, fatigue resistance of 8C is inferior to specimen 24A. This appears to be attributed partly to the peening induced surface damage, as shown in Figure 7. Overall surface damage after shot peening does not differ greatly between 24A and 8C specimen, but careful examination reveals examples of PSEF as indicated by arrows in Figure 7d. The lower value of surface residual stress and the higher half

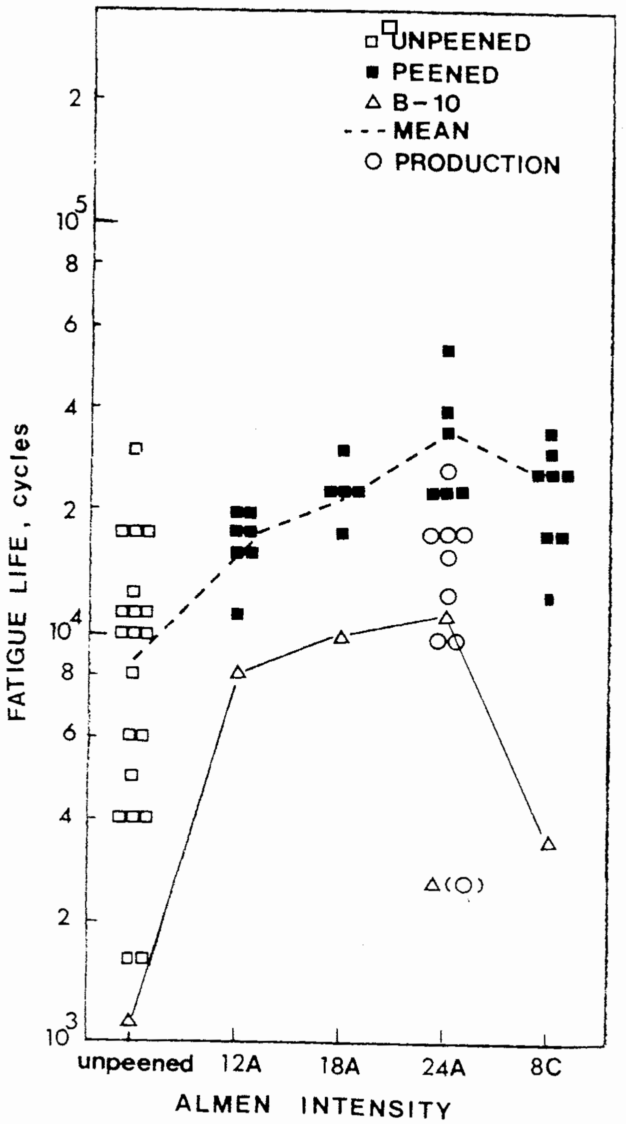

Figure 5. Effect of Almen intensity on fatigue life

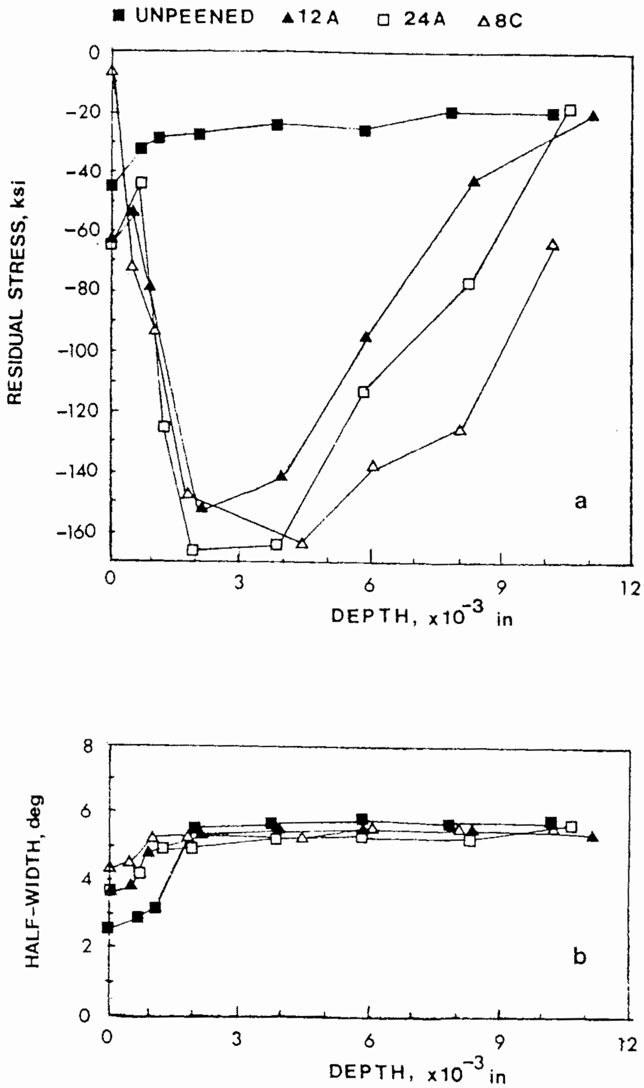

Figure 6. (a) Residual stress and (b) (211) peak width distributions of unpeened and peened gears

Table III. Mean and B-10 Fatigue Lives(Cycles) of Various Specimen Groups

	Unpeened	12A	18A	24A	8C	24A Conv. Peened
Mean	9,850	16,571	23,800	33,167	24,750	16,375
B-10	1056	7,708	11,512	11,953	3,568	2,663

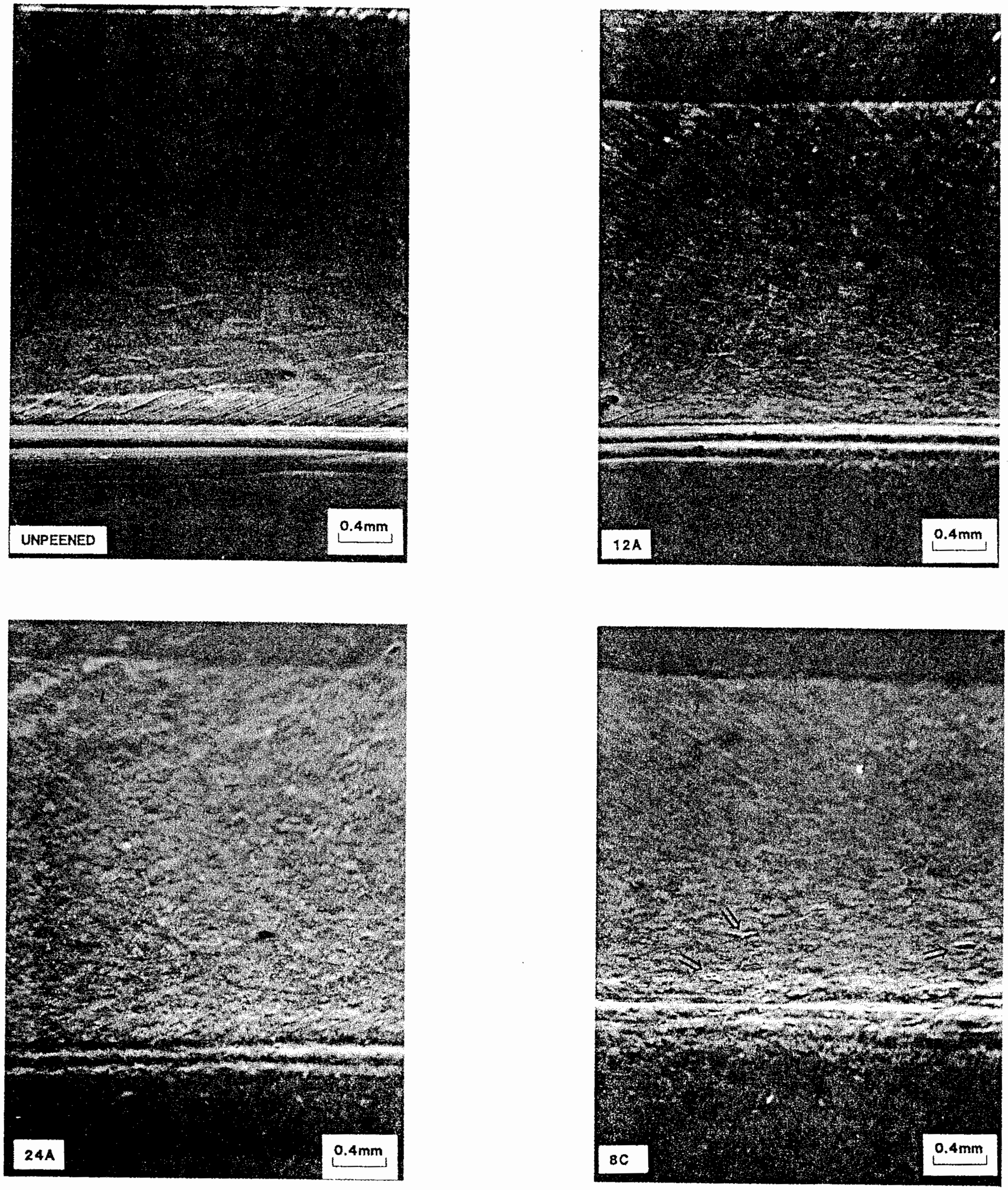

Figure 7. Unpeened(as machined) surface and surface damage induced by shot peening at various Almen intensity

width of (211) diffraction peak observed in specimen 8C are also evidence of the higher amount of plastic deformation on the surface. Presumably, PSEF's acted as stress concentrators causing early initiation of fatigue cracks. However, the degree of PSEF is much smaller compared with the observations made in the previous studies[3, 7]. This appears to be due to the high hardness of the carburized surface.

For the unpeened gear, the maximum compressive stress as a result of heat treatment is on the surface and decreases in magnitude with increasing depth. The half width of (211) diffraction peak shows a substantial reduction in magnitude near the surface when compared with peened gears. This indicates the lack of peening induced plastic deformation.

CONCLUSIONS

1. The optimum Almen intensity is close to 24A with S-230 steel shots in a 54-60 HRC hardness range.
2. Mean fatigue life of optimum peened gears increased by more than 200% when compared with unpeened gears at a very high test load.
3. Optimum peened gears improved the mean and B-10 fatigue life by 100% and almost 350%, respectively, compared with conventionally peened production gears at a very high test load.
4. The improved fatigue life for 24A peened gears is attributed to the highest compressive residual stress incurred.
5. The shorter fatigue life in 8C peened gears indicates that overpeening is possible due to the fact that optimum fatigue strength is a balance between residual stresses and surface damage induced by shot peening.

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