# PREDICTION OF FATIGUE STRENGTH OF SHOT-PEENED AND THEN GROUND SPECIMENS

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## ABSTRACT

In this paper a new concept of shot-peening strengthening, internal fatigue strength, is advanced. According to the internal fatigue strength of the target material, a method for prediction of fatigue strength of the peened and then ground specimens is proposed and described in detail. The method mainly includes calculation of the compressive and tensile residual stress field, determination of the internal fatigue strength, and prediction of the nominal fatigue strength of the peened specimen . Experimental verification is carried out with 40 Cr steel specimens under different heat treating and peening conditions . The results of verification show that the prediction method is both simple and accurate .

## KEYWORDS

Shot peenig , Residual stress, Fatigue strength

## NOMENCLATURE

| | |
|---|---|
| $\sigma_{max}$ | Maximum resultant tensile stress |
| $\sigma_c$, $\sigma_t$ | Compressive and Tensile residual stress |
| $\sigma_{cs}$ | Compressive residual stress at surface |
| $\sigma_{cm}$ | Maximum compressive residual stress |
| $\sigma_{tm}$ | Maximum tensile residual stress |
| $\sigma_{1(tm)}$ | Applied stress at the point where $\sigma_{tm}$ occurs |
| FS | Fatigue strength for $a \times 10^6$-cycle life under three-point bending with stress ratio of 0.05 |
| IFS | Internal fatigue strength |
| SFS | Surface fatigue strebgth, i.e.,fatigue strength of target material under as-heat treated condition |
| $Z_0$ | Thickness of compressive residual stress layer introduced during shot peening |
| $Z_{cm}$ | Depth of point where $\sigma_{cm}$ occurs |
| $Z_{tm}$ | Depth of point where $\sigma_{tm}$ occurs |
| $Z_s$ | Depth of point where fatigue source occurs |
| $\sigma_s$, $\sigma_b$ | Yielding and Ultimate tensile strength of target material |
| D,$D_d$ | Average diameter of steel shots and peening dents |
| C | peening coverage rate ($\times$100%) |
| h | Thickness of specimen |
| $\alpha$ | Ratio of IFS and SFS |
| F | Equivalent load during peening |

## INTRODUCTION

It has been noticed that when the surface of a shot peened specimen is ground a little or the peening intensity is lower,the crack initiation location during three point bending fatigue test is nearly always in the inside of the specimen and within the tensile residual stress zone[1,2]. The critical fatigue stress of material in the interior, i.e., internal fatigue strength (IFS) is enormously higher than the fatigue strength of un-peened specimen,i.e.,surface fatigue strength(SFS). IFS, as being proposed by the authors[3,4],is an intrinsic property of material and is independent of shot peening regime. Experimental and calculaled data showed that the ratio of IFS and SFS is about equal to 1.35. IFS determined by the ratio and SFS of a material can be used to predict the apparent or nominal fatigue strength (FS) of peened and the ground specimens. In this paper a method for prediction of fatigue strength in such case is preposed and the predicted results are verified by experiments.

## PREDICTION METHOD

### Main Train of Thought

As mentioned above, fatigue failures of peened and then ground speciments nearly always start in the tensile residual stress zone. Because of the statistical nature of fatigue,the exact position of fatigue source can not be determined before testing. But from safety consideration, it is reasonable to assume that the failure will begin at the position where maximum resultant tensile stress $\sigma_{max}$ (which is equal to the sum of local applied stress and local tensile residual stress there) occurs and reaches the internal fatigue strength of target material. Then, if the gradient of applied stress is very small, the criterion of fatigue failure for peened and then ground specimens can be expressed as

$$\sigma_{max} = \sigma_{tm} + \sigma_{l(tm)} = IFS \tag{1}$$

where $\sigma_{tm}$ is the peak value of tensile residual stress, and $\sigma_{l(tm)}$ is the applied stress at the point where $\sigma_{tm}$ occurs. According to Eq.(1), if the IFS of target material and $\sigma_{tm}$ under given peening condition are know, the $\sigma_{l(tm)}$ and then the nominal fatigue strength of specimen,FS,can be calculated

$$\sigma_{l(tm)} = IFS - \sigma_{tm} \tag{1-1}$$

$$FS = (h / (h - 2Z_{tm}))\sigma_{l(tm)} \tag{2}$$

where h is the thickness of specimen,and $Z_{tm}$ is the depth of point where $\sigma_{tm}$ occurs.

### Calculation of Compressive Residual Stress Field

According to a model proposed by the authors[3,4], in order to calculate the $\sigma_{tm}$ in Eq.(1-1), the compressive residual stress distribution introduced by shot peening should be determined firstly. Two methods for calculation of compressive residual field have been put forward.

Empirical Method.According to authors'work[3],some characteristic parameters of the compressive residual stress field (Fig.1) can be calculated by using following empimical equations.

The compressive residual stress at surface

$$\sigma_{cs} = 114 + 0.563\sigma_s \quad \text{(in Mpa)} \tag{3}$$

The maximum value of compressive residual stress

$$\sigma_{cm} = 147 + 0.567\sigma_b \quad \text{(in Mpa)} \tag{4}$$

The thickness of compressive residual stress layer

$$Z_0 = (1.41D_d - 0.09D)[1 + 0.09(C - 1)^{0.35}] \quad (\text{in } \mu m) \tag{5}$$

The depth of point where $\sigma_{cm}$ occurs

$$Z_{cm} \approx 0.28Z_0 \quad (\text{in } \mu m) \tag{6}$$

In these equations

*$\sigma_s$ and $\sigma_b$ are yielding and ultimate tensile strength of target material(in Mpa);*

D is median diameter of steel shots (in μm);

**$D_d$ is median peening-dent diameter (in μm), which can be obtained by using** tentative peening[3,5]; and

C is peening coverage rate(×100%).

Knowing these parameters, we can determine the distribution of compressive residual stress in the surface layer rather accurately.

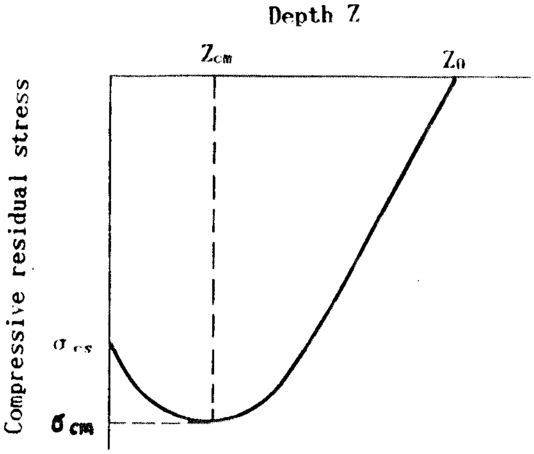

Fig.1 Definition of characteristic parameters of compressive residual stress field

Analytical Method. According to an analytical model proposed by authors[3] , the compressive residual stress distribution with coverage rate of 100% can be determined by using a computer program, if the equivalent load (F) during peening and the tension stress-strain curve of target material are known. F can be calculated from median diameter of shots and peening dents (D and $D_d$) and true stress of target material at necking ($S_b$), as described in Ref [5]. Peening coverage rate (C) has litte influence on other parameters but increases the thickness of the compressive residual stress layer

$$Z_0 = Z_{0(c-1)}[1 + 0.09(C - 1)^{0.35}] \tag{7}$$

where $Z_0(c=1)$ *is the thickness of the compressive stress layer when* C=1.

## Calculation of Tensile Residual Stress

It is very difficult to determine the tensile residual stress experimentally or analytically. On the basis of elastic-plastic finite element analyses, we have obtained a simulating equation expressing the distribution regularity of tensile residual stress[3]:

$$\sigma_t(Z)= (Z - Z_0)^{1.35} / (a(Z - Z_0)^2 + b) \qquad (8)$$

where a and b are two constants which can be determined from following conditions:

$$\int_0^{Z_0} \sigma_c(Z)\, dZ = \int_{Z_0}^{h/2} \sigma_t(Z)\, dZ \qquad (9)$$

and

$$(Z_{tm} - Z_0) / Z_0 = 0.23 \qquad (10)$$

Using Eqs.(8) and (10), we can obtain the value of $\sigma_{tm}$ and $Z_{tm}$ in Eqs.(1-1) and (2).

### Determination of Internal Fatigue strength (IFS) of Target Material

IFS can be calculated from fatigue fest data of one or two groups of peened and then ground specimen. Since IFS is an intrinsic parameter of property of given metal, it can be used to predict the FS of specimens peened under different conditions. But it has been established that the ratio of IFS and SFS, $\alpha$, is approximately equal to 1.35. On the basis of theoritical analyses, it is believed that the fact $\alpha \approx 1.35$ is valid not only for the material used in Ref[4],but also for other materials.Then, a more covenient method to determine IFS may be used, i.e., to calculate IFS according to

$$\text{IFS} = \alpha \cdot \text{SFS} \qquad (11)$$

where $\alpha = 1.35$ .

By using Eqs(1-1),(8),(10) and (11), all main parameters needed can be determined and, then, the nominal fatigue strength (FS) of peened and then ground specimens can be calculated according to Eq.(2).

## EXPERIMENTAL VERIFICATION

The specimens used this work were made of $40C_r$ steel, the mechanical properties of which after quenching and tempering at 200℃ (A) and 550℃ (C) are given in Tab.1. Fatigue specimens of 10×15×50mm were peened and then ground, and then tested under three-point bending condition with load ratio of 0.05 to obtain (nominal) fatigue strength (FS) for $5\times10^6$ cycles life. A tentative peening procedure was carried out to determine $D_d$ in order to calculate equivalent load F during peening. The peening conditions and $D_d$ are also given in Tab.1.

The FS of as-heattreated and un-peened specimens (i.e. the SFS of target material) and those of peened and then ground specimens are listed in Tab.2 and Tab.3. The parameters needed for prediction of FS were determined according to above proposed method and are also listed in Tab.2 and Tab.3. Finally, in the last column of Tab. 2 and Tab. 3, the predicted data of FS of specimens are given. It can be seen from comparison of experimenlal and calculated FS data that nearly all predicted data are

Tab.1 Mechanical Properties and Peening Conditions of Specimens

| Symbol of specimen | Tempering temperature | $\sigma_s$, MPa | $\sigma_b$, MPa | D, mm | Air pressure, MPa | Coverage rate, % | Ground thickness, μm | $D_d$, μm |
|---|---|---|---|---|---|---|---|---|
| A000* | 200℃ | 1420 | 1910 | | | | | |
| A523 | | | | 0.55 | 0.2 | 300 | 0 | 153 |
| A121P20 | | | | 1.10 | 0.2 | 100 | 20 | 271 |
| A143P50 | | | | 1.10 | 0.4 | 300 | 50 | 310 |
| A166P50 | | | | 1.10 | 0.6 | 600 | 50 | 355 |
| C000* | 550℃ | 980 | 1120 | | | | | |
| C523P20 | | | | 0.55 | 0.2 | 300 | 20 | 195 |
| C143P50 | | | | 1.10 | 0.4 | 300 | 50 | 353 |

* as un-peened

very near to, but a little lower than the experimentally determined ones. The results show clearly that the prediction method proposed in this work is successful.

Tab. 2 Experimental and Predicted Data of Nominal Fatigue Strength of Peened and Then Ground Specimens(the compressive residual stress field is determined by using the empirical method)

| Symbol of specimen | Zo , μm | Zs* μm | a $\times 10^{-4}$ | b | Ztm, μm | σ tm MPa | IFS**, MPa | FS, MPa | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Experimental | Predicted |
| A000 | | 0 | | | | | 1430 | $1060^{+}$ | |
| A523 | 177 | 240 | 2.98 | 0.27 | 230 | 196 | | 1320 | 1300 |
| A121P20 | 258 | 360 | 1.92 | 0.40 | 352 | 231 | | 1340 | 1290 |
| A143P50 | 330 | 470 | 1.68 | 0.47 | 406 | 241 | | 1350 | 1300 |
| A166P50 | 418 | 620 | 1.22 | 0.59 | 538 | 276 | | 1360 | 1300 |
| C000 | | 0 | | | | | 1110 | $820^{+}$ | |
| C523P20 | 237 | 275 | 3.71 | 0.52 | 288 | 136 | | 1020 | 1030 |
| C143P50 | 400 | 450 | 2.10 | 0.85 | 491 | 170 | | 1040 | 1040 |

* measured depth of fatigue source

* * calculated by using IFS = 1.35 × SFS

\+ SFS

Tab. 3 Experimental and preauted Data of Nominal Fatigue Strength of Peened and Then Ground Specimens(the compressive residual stress field is determined by using the analytical method)

| Symbol of specimen | Zo , μm | Zs* μm | a $\times 10^{-4}$ | b | Ztm, μm | σ tm MPa | IFS**, MPa | FS, MPa | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Experimental | Predicted |
| A000 | | 0 | | | | | 1430 | $1060^+$ | |
| A523 | 181 | 240 | 3.10 | 0.26 | 222 | 192 | | 1320 | 1300 |
| A121P20 | 270 | 360 | 2.02 | 0.38 | 332 | 228 | | 1340 | 1290 |
| A143P50 | 334 | 470 | 1.69 | 0.48 | 410 | 236 | | 1350 | 1300 |
| A166P50 | 438 | 620 | 1.26 | 0.61 | 538 | 267 | | 1360 | 1310 |
| C000 | | 0 | | | | | 1110 | $820^+$ | |
| C523P20 | 240 | 275 | 3.69 | 0.54 | 295 | 135 | | 1020 | 1030 |
| C143P50 | 420 | 450 | 1.85 | 0.83 | 517 | 187 | | 1040 | 1030 |

* measured depth of fatigue source

* * calculated by using IFS = 1.35 × SFS;     + SFS

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