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Overall Evaluation of the Effect of Residual Stress Induced by Shot Peening in the Improvement of Fatigue Fracture Resistance for Metallic Materials

WANG Renzhi[1] and RU Jilai[2, *]

1 *Metal Physics Laboratory, Beijing Institute of Aeronautical Materials, Beijing 100095, China*
2 *Metal & Chemistry Institute, China Academy of Railway Science, Beijing 100081, China*

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Abstract: Before 1980s, the circular suspension spring in automobile subjected to torsion fatigue load, under the cyclic normal tensile stresses, the majority of fatigue fracture occurred was in normal tensile fracture mode(NTFM) and the fracture surface was under 45° diagonal. Because there exists the interaction between the residual stresses induced by shot peening and the applied cyclic normal tensile stresses in NTFM, which represents as “stress strengthening mechanism”, shot peening technology could be used for improving the fatigue fracture resistance(FFR) of springs. However, since 1990s up to date, in addition to regular NTFM, the fatigue fractures occurred of peened springs from time to time are in longitudinal shear fracture mode(LSFM) or transverse shear fracture mode(TSFM) with the increase of applied cyclic shear stresses, which leads to a remarkable decrease of FFR. However, LSFM/TSFM can be avoided effectively by means of shot peening treatment again on the peened springs. The phenomena have been rarely happened before. At present there are few literatures concerning this problem. Based upon the results of force analysis of a spring, there is no interaction between the residual stresses by shot peening and the applied cyclic shear stresses in shear fracture. This means that the effect of “stress strengthening mechanism” for improving the FFR of LSFM/TSFM is disappeared basically. During shot peening, however, both of residual stress and cyclic plastic deformed microstructure are induced synchronously like “twins” in the surface layer of a spring. It has been found for the first time by means of force analysis and experimental results that the modified microstructure in the “twins” as a “structure strengthening mechanism” can improve the FFR of LSFM/TSFM. At the same time, it is also shown that the optimum technology of shot peening strengthening must have both “stress strengthening mechanism” and “structure strengthening mechanism” simultaneously so that the FFR of both NTFM and LSFM/TSFM can be improved by shot peening.

Keywords: shot peening strengthening principle, fatigue fracture resistance, strengthening mechanisms of fatigue fracture, classification on fatigue fracture mode

1 Introduction

With the rapid development of automobile industry, for the circular spring mainly referring to suspension and clutch springs etc. subjected to torsion fatigue load, the majority of fractures are fatigue fracture including mechanical and corrosion fatigue fracture under the cyclic stresses. Among the total number of fracture failure, fatigue fracture has the highest percentage approximate 60%–90%. All the fractures happened in the metallic materials/springs whether they are fractured by static load or by fatigue load are all in the following three basic modes: ①opening mode (mode-Ⅰ), ②edge-sliding mode (mode-Ⅱ), and ③tearing mode (mode-Ⅲ). The macroscopic fracture pattern of normal tensile fracture mode (mode-Ⅰ) under applied cyclic normal stresses and the macroscopic pattern of three fracture modes (mode-Ⅰ, mode-Ⅲ and mode-Ⅱ) under applied cyclic shear stresses are given in Fig. 1. and Fig. 2. respectively.

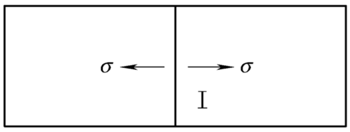
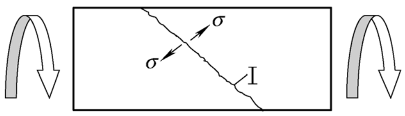
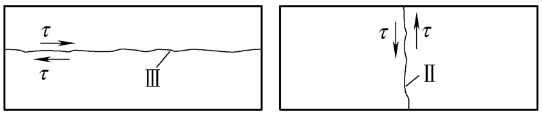


Fig. 1. Sketch of NTFM (mode-Ⅰ) with applied cyclic normal stress



(a) NTFM(mode - Ⅰ)



(b) LSFM(mode -Ⅲ) (c) TSFM(mode - Ⅱ)

Fig. 2. Sketch of macroscopic morphology of three modes with applied cyclic shear stress

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* Corresponding author. E-mail: rujilai@qq.com

Before 1980s, the majority of fatigue fractures of springs subjected to torsion fatigue load were in normal tensile fracture mode(NTFM). However, in the past decade or two, the fatigue fracture occurred of shot peened springs (diameters in $\Phi 9$–$\Phi 16$ mm especially) from time to time are in longitudinal shear fracture mode(LSFM) or transverse shear fracture mode(TSFM) in addition to regular NTFM with the increase of applied cyclic shear stresses. For springs fractured in LSFM/TSFM, their FFR decreased remarkably. Once a shear fracture occurred, "twice" shot peening treatment was used again on the "once" peened springs. The surface residual stresses induced by "once" and "twice" shot peening are 800 MPa and 850 MPa respectively. The increase of residual stress is only 6.3% which means both values of residual stresses are almost the same. However, the fracture mode of springs with twice shot peening reversed to NTFM from LSFM/TSFM and the FFR increased greatly. Consequently, the specified fatigue life of springs can be reached.

Among the three fracture modes, the FFR(or fracture life) of springs subjected to torsion fatigue load is the highest with NTFM. On the condition of lower applied cyclic shear stress(for example, before 1980s), the majority of fatigue fracture occurred in NTFM. Therefore, shot peening technology was often used to improve FFR of springs by means of inducing residual compressive stresses in the surface layer. In fact, the earliest use of shot peeening for improving fatigue performance historically was on springs[1]. The residual stresses by shot peening has been considered to play a leading role on fatigue performance all the time[1–3]. However, if the fracture mode is LSFM/TSFM instead of NTFM, the fatigue life of springs is decreased. It is evident that there are a lot of questions about fatigue fracture stated above. For example, under almost the same residual stress by shot peening, why the LSFM/TSFM with shorter fatigue life should occur sometimes? What are the factors determining or influencing fatigue fracture mode? Is there any other new strengthening mechanism for improving shear fatigue fracture life in the shot peening technology? Up to now, there are only a few literatures concerning LSFM/TSFM. But no literature has been found about the problems mentioned above. It is the theme that the authors intend to research and expound in this paper.

2 Classification of Fatigue Fracture

2.1 Methods of fatigue fracture classification

Traditionally, the fatigue fracture classification includes the methods according to the controlled applied stress amplitude/strain amplitude(including loading frequency), according to the loading method(loading type) and according to the environment condition etc.

A new classification method is suggested by the authors according to the following macroscopic fatigue fracture modes:

Fatigue fracture in NTFM, i.e. (mode-Ⅰ);

Fatigue fracture in LSFM, i.e. (mode-Ⅲ);

Fatigue fracture in TSFM, i.e. (mode-Ⅱ).

Which kind of fracture mode occurred in the testing or in service is the function of variables of applied loading method, load level and mechanical behavior of the material and so on.

Classification according to the macroscopic fracture mode makes it possible to avoid any confused concept and one-sided misunderstandings about fatigue fracture mechanism to evolve. Furthermore, on the basis of correct understanding fatigue fracture mode resulted from different fatigue fracture mechanism, the purpose of increasing FFR corresponding to its fracture mode can be achieved by employing the right surface deformation strengthening mechanism. That is what to be discussed in the present paper.

2.2 Two fatigue fracture modes of both normal tensile stress and shear stress

2.2.1 Fatigue fracture mode due to normal stress—NTFM

Tension-tension or tension-compression fatigue, bending fatigue, rotating bending fatigue are all belong to NTFM. Under certain loading conditions, torsion fatigue fracture may be occurred in NTFM. It is because of the fact that the most fatigue fractures among the frequently met fatigue fracture events are NTFM, might bring about some of the following misunderstandings in people's mind:

(1) All the fatigue fractures are mistakenly considered to be NTFM;

(2) On the other hand for NTFM of fatigue fracture, the crack propagation under a 45° angle with fatigue shear fracture mode at the early stage of crack initiation (often called the first stage of propagation) is often neglected;

(3) So far, a lot of people still have a wrong idea regarding the "stress strengthening mechanism" as the only factor controlling the FFR[4–8]. They simply ignore or not at all know that the FFR could mainly be controlled by "structural strengthening mechanism" under a specific (definite) condition.

2.2.2 Fatigue fracture modes due to torsion shear stress —NTFM, LSFM and TSFM

There may be three modes of fatigue fracture caused by the torsion shear stress. They are NTFM, LSFM and TSFM. The torsion fatigue fracture mechanism map composed of 4 variables namely torsion yield strength, applied shear stress amplitude, fatigue fracture life and fracture mode is schematically illustrated in Fig. 3[9–10]. It has been shown that the fracture may occur sequentially in three different modes(NTFM, LSFM, TSFM) according to the changes of loading method, load level and shear yield strength of a material only under the condition of pure torsion.

According to Fig. 3, the map of reverse torsion fatigue fracture mechanism of high strength steel, and a large number of the authors' experimental results[11–13], the torsion fatigue fracture rules of metal materials/parts can be formulated as follows:

(1) The torsion fatigue strength is increased with the rising of static strength(Microhardness *HV*, Tensile strength σ_b, Shear yield strength τ_s) of a material itself;

(2) The FFR is decreased with the rising of applied cyclic shear stress(τ). Furthermore, there is the highest FFR with NTFM and the lowest FFR with TSFM;

(3) On the condition of the same static strength of materials/parts, with the rising of the applied cyclic shear stress(τ), the fracture mode changes from normal tensile fracture mode to shear fatigue fracture mode with the sequence of NTFM→LSFM→TSFM;

(4) It is pointed out from the rules of torsion fatigue fracture mode mentioned above that the FFR of shear fracture mode depends firstly on applied cyclic shear stress (τ) level, and secondly on the mechanical properties of a material itself(*HV*, σ_b, τ_s).

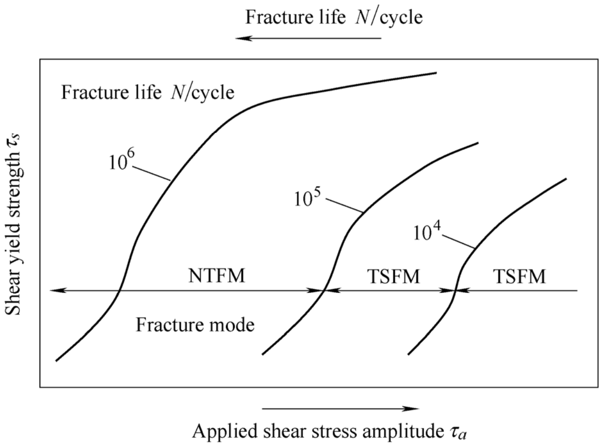

Fig. 3. Sketch map of fatigue fracture mechanism with three fracture modes under applied cyclic torsion stress

3 Surface Strengthening Technology Used for Improving Fatigue Fracture Resistance of Metal Materials/Parts

The surface strengthening technology used in the present paper is the surface shot peening deformation strengthening technology. The principle of shot peening is elaborated as follows.

Shot peening is a surface strengthening technology in which a high velocity jet of shot particles impacts the target material and both of residual stresses and cyclic plastic deformed microstructure as a “twins” are induced synchronistically in the surface layer of the target material during the non-uniform cyclic plastic deformation process. It can be seen in the following discussion that either of the “twins” (namely residual stress and cyclic plastic deformed microstructure) could play a main role in the improvement of FFR under certain fracture mode.

The subclause1.1 scope of AMS-S-13165[5] and MIL-S-13165C[6], stated “This specification covers procedure requirements for shot peening of metal parts, to induce residual compressive stresses in specified surfaces, for the purpose of improving resistance to fatigue, stress corrosion cracking, and galling.”

It is clear, the subclause 1.1 scope of Refs. [5] and [6] could be understood this way: the residual compressive stresses(normal stress) induced by shot peening is nothing but the only strengthening mechanism for improving FFR of all fracture modes. That is to say, the strengthening effect of the cyclic plastic deformed microstructure due to shot peening has been neglected completely. In fact, the modified microstructure by shot peening is the other main strengthening mechanism for improving the FFR in the LSFM/TSFM.

The scientificity and correctness of the authors argumentation stated above will be discussed and verified based upon the force analysis of a material/spring and the effect of the modified cyclic plastic deformation microstructure induced by shot peening.

4 Discussion on the “Structure Strengthening Mechanism” due to Shot Peening

4.1 Force analysis of a cylinder unit cell subjected to axial cyclic normal stress(σ) and residual stress(σ_r) in any section

The cyclic normal stress σ acted in the axial(x) direction of cylinder unit cell and the residual compressive stresses σ_r by shot peening are shown in Fig. 4. η and ζ of the reference coordinates is assumed perpendicular to and parallel to the diagonal section respectively and the angle between the reference coordinates and xy coordinates is α.

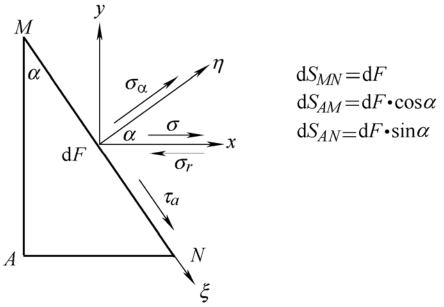

Fig. 4. Force analysis diagram on any diagonal section of cylinder cell (the thickness of the cell is 1) under the action of applied cyclic normal stress(σ) and residual stress(σ_r) induced by shot peening

Two equilibrium equations of forces P are as follows:

$$\Sigma P_\eta=0,\ \Sigma P_\zeta=0.$$

The formulas for calculating the normal stress component and shear stress component acting on the diagonal section can be given as follows:

$$\sigma_\alpha=(\sigma_r-\sigma)\cos^2\alpha,$$

$$\tau_\alpha=\frac{1}{2}(\sigma_r-\sigma)\sin 2\alpha.$$

The value of the normal stress component and shear stress component acting on the diagonal sections under a specified angle calculated using these two formulas are listed in Table 1.

Table 1. Calculated two stress components σ_α and τ_α acting on four specific diagonal sections

Angle $\alpha/(°)$	Normal stress component σ_α/MPa	Shear stress component τ_α/MPa
0	$\sigma_r - \sigma$	0
45	$1/2(\sigma_r - \sigma)$	$1/2(\sigma_r - \sigma)$
90	0	0
135	$1/2(\sigma_r - \sigma)$	$-1/2(\sigma_r - \sigma)$

For NTFM, when normal line of fracture surface is basiclly parallell to the dirction of cyclic normal stress or the angle between them is $\alpha \approx 0$, the cyclic normal stress component acting on the section is $\sigma_\alpha = (\sigma_r - \sigma)$. This indicates that resultant normal stress component σ_α is reduced after the interaction between the residual stress by shot peening and the applied cyclic normal stress, thus resulted in the improvement of FFR of the material/part. It is the strengthening effect of residual compressive stress for improving the FFR of NTFM, or in other words that is the "stress strengthening mechanism". In addition, the interaction between the residual stress by shot peening and the applied cyclic normal stress could effect a change in shear stress component too. In this condition, if fatigue cracking of a material/part initiated, the angle between the normal line of fracture surface and the direction of cyclic normal stress is 45° or 135°.

4.2 Force analysis of a cylinder unit cell subjected to cyclic shear stress(τ) and residual stress(σ_r) in any section

Applied cyclic shear stress(τ) and residual compressive stresses σ_{r} by shot peening acting on cylinder unit cell are shown in Fig. 5. η and ζ of the reference coordinates is assumed perpendicular to and parallel to the diagonal section respectively and the angle between the reference coordinates and xy coordinates is α.

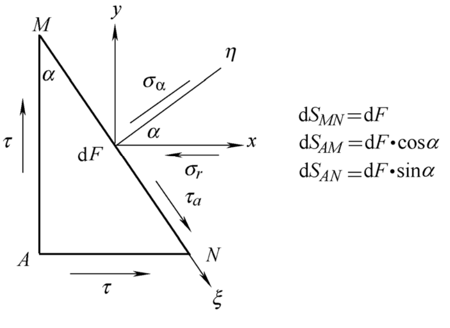

Fig. 5. Force analysis diagram on any section of cylinder cell(the thickness of the cell is 1) under the action of applied cyclic shear stress(τ) and residual stress(σ_r) induced by shot peening

Two equilibrium equations of forces P are as follows:

$$\Sigma P_\eta = 0,\ \Sigma P_\zeta = 0.$$

The formulas for calculating the normal stress component and shear stress component acting on the diagonal section can be given as follows:

$$\sigma_\alpha = \sigma_r \cos^2 \alpha - \tau \sin 2\alpha,$$

$$\tau_\alpha = \frac{1}{2}\sigma_r \sin 2\alpha + \tau \cos 2\alpha.$$

The value of the normal stress component and shear stress component acting on the diagonal sections under a specified angle calculated using these two formulas are listed in Table 2.

Table 2. Calculated two stress components σ_α and τ_α acting on four specific diagonal sections

Angle $\alpha/(°)$	Normal stress component σ_α/MPa	Shear stress component τ_α/MPa
0	σ_r	τ
45	$1/2\sigma_r - \tau$	$1/2\sigma_r$
90	0	$-\tau$
135	$1/2\sigma_r + \tau$	$-1/2\sigma_r$

Several important revelations can be obtained from the calculated results of Table 2.

(1) When applied cyclic shear stress τ is relatively low and the fatigue fracture mode is NTFM under the action of normal stress component σ_α, the residual stress by shot peening has strengthening effect and the fracture surface is in the diagonal section under an angle of α=45° or 135°. However, once the applied cyclic shear stress τ is kept increasing to a certain value, the fracture mode will change from NTFM to LSFM/TSFM and the fracture surface is in the longitudinal or transverse section under an angle of α=0° or 90° in which the residual stress by shot peening no longer interacts with the shear stress τ(see line 1 and line 3 in Table 2. This means the strengthening effect of residual stresses by shot peening for improving the shear fracture mode is weakened greatly, or in other words, the strengthening effect of residual stresses has been basically disappeared.

(2) At a higher shear stress component τ_α, the fracture mode changes from NTFM to LSFM/TSFM and the strengthening mechanism provided by the residual stresses has been basically disappeared. In this case what would have been the key strengthening mechanism for improving the FFR of the shear fracture mode instead of "stress strengthening mechanism"?

As stated above, the FFR of NTFM is increased by the interaction of residual compressive stress with applied cyclic normal stress, which leads to the reduction of cyclic normal stress σ_α. However, for the FFR of LSFM/TSFM, it is impossible to introduce a shear stress with the opposite direction to the applied cyclic shear stress by means of shot peening. In this case, the improvement of the FFR of LSFM/TSFM by shot peening is contributed to the plastic deformed microstructure, the other element of the "twins", rather than the residual compressive stresses, because the modified microstructure(namly cyclic plastic hardening microstructure) by shot peening increases the mechanical properties of a material, mainly refering to the shear yield strength(τ_s) in particular.

It has been confirmed in recent years by a number of fatigue experiments reported in references[11–13] that the shear yield stress τ_s in the material surface layer could be increased up to more than 80% by an optimized shot peening treatment. The curves change in Fig. 3 shows that under a constant applied shear stress τ_a , the fracture life will be extended as the shear yield strength τ_s increased. This is to say that the FFR will be inreased with τ_s increasing.

(3) The most significant discovery obtained from the force analysis of torsion fatigue is that, for the researchers studying shot peening in the field of material science for more than half a century, no one up to now is able to separate the "twins" by shot peening completely so as to do research to find out the contribution of the residual stresses or plastic deformed microstructure about its strengthening effect alone on the FFR. When investigating on the factors influencing torsion FFR from a new point of view, (for example, the research on circular coil spring subjected to torsion cyclic stress), it is found through force analysis that the "twins" of the residual stresses and the deformed microstructure by shot peening have been already separated automatically at the definite angle range: one is the residual stresses; the other is the cyclic shear stresses (τ) which is directly related to the cyclic deformed microstructure. From point of view considering engineering material, the angle of normal line at definite sections of shear fatigue fracture is not only a single angle, but a angle with a small range, for example α=0°±5° and 90°±5°. A few angle fluctuation metioned above for the cyclic shear stresses has only a negligible influence to the cyclic shear stresses value, or in other words, the virgin plastic deformed microstructure is not affected basically by the residual stresses. This microstructure mentioned above, as a matter of fact, plays the role of structure strengthening for improving torsion FFR, which is called "structure strengthening mechanism." It becomes the dominant strengthening mechanism for improving the FFR of the LSFM/TSFM instead of "stress strengthening mechanism".

For NTFM, the role of residual stresses(σ_r) is to "force" the FFR to increase by the interaction with applied cyclic stress(σ). However, for LSFM/TSFM, the modified microstructure increases the shear yield strength of the material itself so as to force the FFR to increase.

All points stated above elaborate the essence of "structure strengthening mechanism". It is the increased shear yield strength τ_s of the material owing to the microstructure modification after plastic deformation that increses the FFR or fracture life. As for the details of how the LSFM/TSFM reverse drive to NTFM could be found elsewhere in Fig. 13 of Ref. [14].

5 Conclusions

(1) "Stress strengthening mechanism" in shot peening principle is neither the only one nor the omnipotent strengthening mechanism, which can be basically used for improving FFR of NTFM.

(2) When τ_a increases or approaches to the τ_s of materials, the fatigue enters the shear fracture mode in which LSFM/TSFM is forced to occur. In this case, the strengthening effect of the "stress strengthening mechanism" is basically dispeared. Based on the force analysis of springs, for the first time the authors pointed out, the major effect for imporving the FFR in shear fracture mode is no longer the "stress strengthening mechanism" but the "structure strengthening mechanism" instead. It is the limitation that the residual compressive stresses have played in the improvement of shear fatigue fracture resistence.

(3) The optimum technology of shot peening strengthening must have both "stress strengthening mechanism" and "structure strengthening mechanism" simultaneously so that the FFR of both NTFM and LSFM/TSFM can be improved by shot peening.

(4) The specifications of AMS-S-13165, MIL-S-13165C as well as another series of similar standards and specifications acknowledged only the "stress strengthening mechanism" and ignored completely the existence and effect of "structure strengthening mechanism". It appears to be at least one-sided misunderstanding about shot peening strengthening principle. The documents mentioned above certainly play a misleading role on the aspect of how to improve FFR for parts subjected to torsion fatigue like circular coil springs and torsion shafts.

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Biographical notes

WANG Renzhi, born in 1932, is a professor at *Metal Physics Laboratory, Beijing Institute of Aeronautical Materials, China*. His main research interests include fatigue and fracture, surface integrity of material, surface strengthening technology and failure analysis for metal parts.
E-mail: 13693064401@163.com

RU Jilai, born in 1962, is currently a senior engineer at *Metal & Chemistry Institute, China Academy of Railway Science*. His main research interests include fatigue and fracture and surface strengthening technology.
E-mail: rujilai@qq.com