JMEPEG (2003) 12:507-511

Another Mechanism for Fatigue Strength Improvement of Metallic Parts by Shot Peening

Yu-kui Gao, Mei Yao, Pei-ge Shao, and Yan-hui Zhao

(Submitted 1 February 2003)

Fatigue crack source in shot-peened specimens may be located either at the surface or in the interior, beneath the hardened layer. In this paper, the mechanism for fatigue strength improvement of shot-peened specimens with internal fatigue crack source was studied. Un-peened and shot-peened specimens made of quenched and low-temperature tempered 40CrNi2Si2Mo2V steel were used. The fatigue crack source in shot-peened specimen is found in the interior beneath the hardened layer. X-ray diffraction analyses of both kinds of specimen fatigue tested at stress equal to their apparent fatigue limit show that obvious changes have taken place in the surface layer for un-peened specimens, while for shot-peened specimens, such changes are observed in the sub-surface layer beneath the hardened layer. The calculated actual critical stress at the fatigue source position (the "internal fatigue limit") for shot-peened specimen is about 138% of the (surface) fatigue limit of un-peened specimen. According to an analysis about the micro-meso-processes of fatigue crack initiation in metals, a concept of "internal and surface fatigue limits of metal" has been proposed. It is believed that the fatigue crack source transfers into the interior, Also, the internal fatigue limit of metal is higher than its surface fatigue limit, and is another mechanism for the improvement of apparent fatigue limit of shot-peened specimen.

Keywords: fatigue limit, shot peening, x-ray diffraction

1. Introduction

The creation of compressive residual stress field in the surface region is a main reason for improvement of long-life fatigue strength ("fatigue limit") of metallic parts after shot peening.[1-4] However, the fatigue crack initiation sites ("fatigue crack sources") in shot-peened specimens are often located in the internal area beneath the hardened layer, where the matrix metal has not been hardened and the tensile residual stress exists. Unexpectedly, the fatigue limit improvement still occurs even in these cases and is often optimal. This phenomenon is difficult to understand only from the beneficial effect of induced compressive residual stress field. To clarify the mechanism of the above-mentioned problem, several studies[5-10] had been undertaken and the present work further studies this topic.

2. Material, Experimental Procedures, and Results

Fatigue specimens with dimensions of 15 (height) × 20 (width) × 130 (depth) mm made of 40CrNi2Si2Mo2V steel (0.39C-0.91Cr-1.82Ni-1.61Si-0.69Mn-0.42Mo-0.07V) were quenched from 870 °C in oil and tempered at 300 °C. The average diameter of original austenite grains of the specimens is 11 μm and the mechanical properties are given in Table 1. Parts of specimens were properly shot-peened (with Almen strip A arc height of 0.3 mm and coverage of 120%) on a pneumatic machine.

Table 1 Mechanical Properties of 40CrNi2Si2Mo2V Steel After Quenching and Tempering

YS, MPa	UTS, MPa	Elongation, %	Reduction of Area, %	Hardness, HRC
1642	1950	12.3	52.9	48

All specimens were ground and polished. Three-point bending fatigue tests with stress ratio of 0.05 were carried out on a high-frequency fatigue test machine and "apparent" fatigue limit for 1×10^7 cycles of both kinds of specimen was determined according to an up-and-down method.[12] It is 1115 MPa for un-peened specimen and 1490 MPa for shot-peened specimen. The word "apparent" is mainly used for the shot-peened specimens because, in this case, the determined fatigue limit is a comprehensive reflection of the properties of matrix metal and the effects induced by shot peening.

Fracture surfaces of broken specimens tested under the stress level a little higher than the apparent fatigue limit and with a fatigue life of about 5×10^5 cycles were analyzed by SEM and the distances of fatigue sources from the surface, Z_s, were determined. The fatigue sources are always located at the surface for un-peened specimens, while, for shot-peened specimens, they are located in the interior with a depth of about 0.22-0.25 mm. Figure 1 shows a typical one with depth of 0.23 mm for peened specimens.

The residual stress of shot-peened specimens was determined by using an x-ray diffraction method with Cr $K_\alpha$radiation and a step-by-step electro-polishing method.[11] The distribution curves of compressive residual stress before

Yu-kui Gao, Beijing Institute of Aeronautical Materials, Beijing 100095, P.R. China; and **Mei Yao, Pei-ge Shao,** and **Yan-hui Zhao**, Institute of Materials Science and Chemical Engineering, Yanshan University, Qinhuangdao 066004, P.R. China. Contact e-mail: joyluke@21cn.com or yukui.gao@biam.ac.cn.

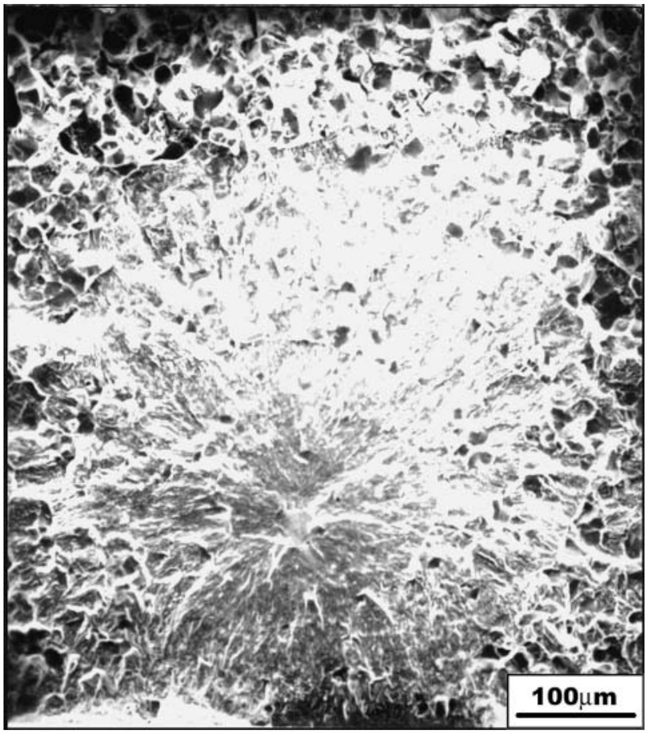

Fig. 1 Fatigue fractograph of shot-peened specimen

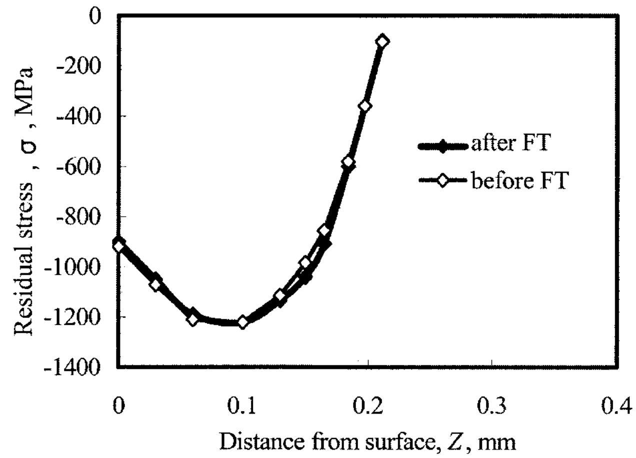

Fig. 2 Compress residual stress fields of shot-peened specimens before and after fatigue testing (FT)

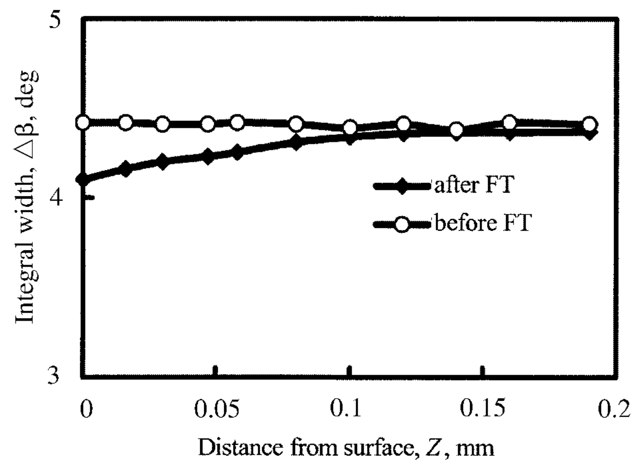

Fig. 3 Distributions of integral width of (211) x-ray diffraction line Δβwith depth **Z** for un-peened specimens, before and after fatigue testing (FT)

and after fatigue testing are shown in Fig. 2. The depth of the compressive residual stress field is about 0.2 mm, which is a little lower than that of the fatigue crack source.

To clarify the microstructure changes during fatigue crack source formation, the integral width, Δβ, of the x-ray diffraction line for crystal plane {211} in the specimens before and after fatigue testing at stress levels equal to their apparent fatigue limit were determined. The distribution curves of β for un-peened specimens and shot-peened specimens are shown in Fig. 3 and 4, respectively.

3. Analyses and Discussions

3.1 Calculation of Local Critical Stress for Fatigue Crack Source Formation ("Internal Fatigue Limit") of Shot-Peened Specimen

Two important differences should be noticed between un-peened and shot-peened specimens. First, the apparent fatigue limit of shot-peened specimens is higher than that of un-peened ones. Second, the fatigue crack sources for shot-peened specimens are located in the interior with the depth a little larger than that of the compressive residual stress field. In contrast, the fatigue crack sources for un-peened specimens is always at the surface. In shot-peened specimens studied in our work, the fatigue crack source formation does not occur within the compressive residual stress zone and the fatigue limit improvement should not be attributed to the beneficial effect of compressive residual stress. The geometric effect, which decreases the actual stress at the position of fatigue source for about 5% only, should also not be the main reason for fatigue limit improvement. Therefore, the improvement of apparent fatigue limit after shot peening should be related to the transfer of fatigue crack source from the surface to the interior. The actual critical stress for fatigue crack source formation in the interior, σ_{wi}, or "internal fatigue limit" is very different from actual critical stress for fatigue crack source formation at the surface, σ_{ws}, or "surface fatigue limit." The σ_{wi} can be calculated according to the following critical condition:

$$\sigma_{wi} = \sigma_{pi} + \sigma_{ri} \qquad \text{(Eq 1)}$$

where σ_{pi} is the local applied stress of specimen at the position of fatigue crack source (0.23 mm from the surface) when the nominal surface stress is equal to the apparent fatigue limit (1490 MPa) of shot-peened specimen. σ_{pi} can be easily determined according to the elastic mechanics law and its value is equal to 1467 MPa for specimens used in this experiment.

σ_{ri} is the local (tensile) residual stress at the position of fatigue crack source. It is related to the compressive residual stress field induced by shot peening and can be determined according to a procedure proposed in Ref. 5. The calculated value of σ_{ri} is about +77 MPa in this work.

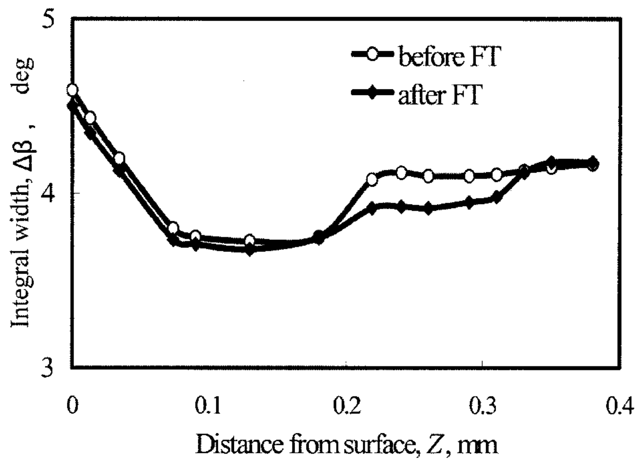

Fig. 4 Distributions of integral width of (211) x-ray diffraction line $\Delta\beta$ with depth $\mathbf{Z}$ for shot-peened specimens, before and after fatigue testing (FT)

Then, the σ_{wi} of used steel is 1544 MPa. It is 1.38 times the fatigue limit of specimen without shot peening, which is the fatigue limit of tested material in common sense and is called "surface fatigue limit," $\sigma_{ws,}$ because the fatigue crack source for un-peened specimen is always located at the surface.

Based on the above-mentioned analyses, the main reason for the improvement of apparent fatigue limit of shot-peened specimen studied in this work is the transfer of the fatigue source from the surface to the interior and the internal fatigue limit of the metal is higher than its surface fatigue limit.

3.2 Relationship Between Fatigue Crack Source Formation and "Meso-Yielding "

To better understand the concept of "surface/internal fatigue limit," it is worthy noticing the experimental results shown in Fig. 3 and 4. In Fig. 3, which is obtained on un-peened specimen, a narrowing effect of integral width $\Delta\beta$ of x-ray diffraction line for crystal plane {211} is observed in the surface layer before and after fatigue testing near a stress of fatigue limit. Being quenched and low temperature tempered, 40CrNi2Si2Mo2V steel is a "cyclic softening" material; then, the narrowing effect of $\Delta\beta$ reflects the decrease of dislocation density in the metal crystals caused by cyclic plastic deformation during fatigue testing. The depth of the affected layer is about 0.14 mm and this region is about 13 times the average diameter of original austenite grains, *d*, of used steel. That is, many grains have taken part in meso-scopical plastic deformation, or "meso-yielding," which has occurred during fatigue testing.

The narrowing effect in the surface layer is also observed in the shot-peened specimen before fatigue testing (Fig. 4). The depth of such a layer is about 0.2 mm, which is approximately equal to the depth of compressive residual stress field. This is a result of repeated plastic deformation during shot peening. After fatigue testing, a further narrowing effect of $\Delta\beta$ is observed. Nevertheless, it occurs not in the surface layer but in the region beneath the hardened layer, with distance from the surface for 0.18-0.32 mm, the width of which is about 12 *d*.

"Meso-yielding" with widths of 12-13 *d* have occurred in both kinds of specimen during fatigue testing. For the un-peened specimens, the meso-yielding zone locates at the surface; for the shot-peened specimens, it locates in the interior and beneath the hardened layer. The fatigue crack source is just located in the zone where the meso-yielding occurs in both kinds of specimen.

The relationship between the fatigue crack source formation and the meso-yielding during fatigue testing can be understood according to an analysis of the initiation and development of fatigue crack.[6,7] As it is known, the fatigue crack initiation is a result of back-and-forth dislocation motions within individual weak grains. Some dislocation models have been proposed to demonstrate the processes for fatigue crack initiation in crystallographic views. But in polycrystalline metals, other important points should be taken into account. First, the grains are randomly oriented and, second, any process related to dislocation motions in individual grains will be restricted by their surrounding grains.

Formation of fatigue crack source in our studies consists of at least 6 steps:[6,7]

1. Dislocation motions within a few weak grains, which will soon be restricted by their surrounding grains.
2. Harmonizing dislocation motions in the surrounding grains, which allow the further dislocation motions in the weak grains.
3. Reverse motion of dislocations in individual weak grains, especially along some favorite slip bands, caused by the restraining effect from surrounding grains during unloading, or under the action of the applied stress during reverse loading.
4. Formation of persistent slip bands with concentrated plastic strain in the weak grains after repeated loading.
5. Formation of fatigue cracks, which will soon be arrested by grain boundaries, along the persistent slip bands.
6. Propagation of one of the initial main cracks across grain boundaries, which also should be considered a probabilistic process.

There are not many new finds in individual steps, but consideration of these processes in the whole can give us an important inspiration that the initiation and propagation of fatigue crack or the formation of fatigue crack source is a process full of probabilistic behavior. Fatigue develops from the processes (called "micro-processes") occurring in individual weak grains or at some weak points (such as non-metallic inclusions), but it occurs must after a series of processes ("meso-processes"), especially the dislocation motion must occur in many grains. This is the basic point of a "micro-meso-process theory" for fatigue crack source formation,[6,7] in which the micro-processes, the meso-processes, as well as the final macroscopical expressions are considered comprehensively.

According to the above-mentioned considerations, it can be concluded that the dislocation motion in many grains or formation of "meso-yielding" areas, in which reverse motion of dislocations may occur during unloading or reverse loading, is a necessary condition for fatigue crack source formation. The narrowing effects of $\Delta\beta$ (Fig. 3 and 4) reflect the formation of meso-yielding zones during fatigue testing and the fatigue crack sources located in these zone.

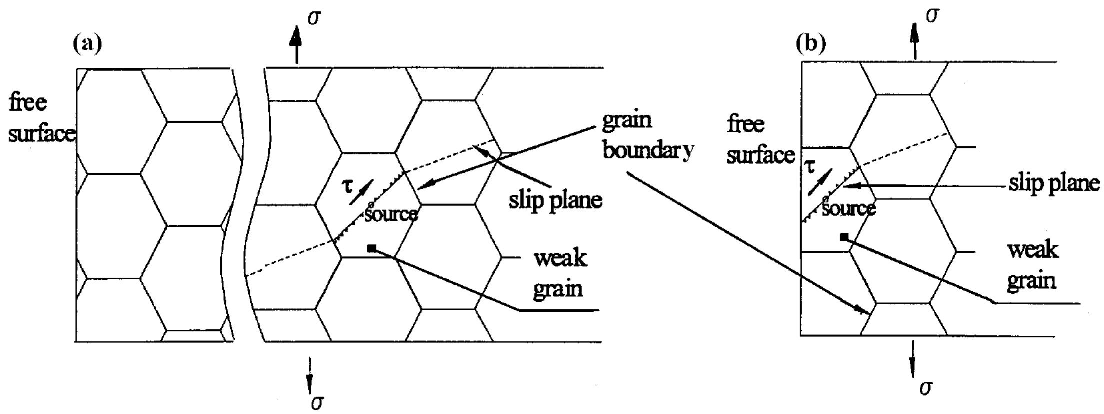

Fig. 5 Schematic diagram of meso-yielding in **(a)** the interior, and **(b)** at surface

3.3 Relationship Between the Surface and the Internal Fatigue Limits

The essence of the "surface fatigue limit," σ_{ws}, and the "internal fatigue limit", σ_{wi}, as well as the relationship between them is discussed here. According to the "micro-meso-process theory" for fatigue crack source formation, it can be easily understood that the fatigue limit actually is the critical stress for occurrence of meso-yielding needed for fatigue crack source formation. In physical and mechanical essence, the processes of "meso-yielding" for fatigue crack source formation are similar to those of macro-yielding. Then, the critical stress for meso-yielding or fatigue limit can be analyzed using the concepts similar to those proposed by Hall[13] for macro-yielding. Under the action of an applied stress, dislocation sources in individual weak grains will operate and generate dislocation loops, which will slip along some given planes and pile up ahead of the grain boundaries. Under the action of the applied stress and the concentrated stress caused by the "piled-ups," dislocation source in the neighboring grains may operate and generate new dislocations. Such harmonizing motions of dislocations in the surrounding grains are the elementary process for meso-yielding, but the critical conditions for occurrence of such processes in the surface layer are different from the ones for occurrence in the interior.

When applied shear stress, τ, is larger than a critical stress, τ_0, for operation of a dislocation source within grain, it will cause the formation of dislocation pile-ups against grain boundaries on both sides. The function of dislocation pile-ups can be substituted by two equivalent dislocations with Burgers vector equal to nb. (n – equivalent numbers of dislocation in every dislocation pile-up). Then, the opposite stress, τ_d, produced by the dislocation pile-up from one side can be expressed as:[13]

$$\tau_d = Gnb/2\pi\,(1-\nu)\,r \qquad \text{(Eq 2)}$$

where G is the shear modulus, ν is the Poisson's ratio, d is the diameter of grain, $r = d/2$ is the distance from dislocation source to grain boundaries.

The τ_d from both sides will counteract the action of applied shear stress at the dislocation source. It will stop to operate, when the following condition are met:

$$\tau_0 = \tau - 2\tau_d \qquad \text{(Eq 3)}$$

Then, in this case, the equivalent number of dislocation in pile-ups, n_i, under the action of a given τ are:

$$n_i = k_{ni}\,(\tau - \tau_0)d \qquad \text{(Eq 4)}$$

where

$$k_{ni} = \pi\,(1-\nu)d/\mathrm{Gb} \qquad \text{(Eq 5)}$$

As mentioned above, the elementary processes for meso-yielding are the operations of dislocation sources in the surrounding grains. This process will occur under the action of stress caused by dislocation pile-up, which is believed to be proportional to $n(\tau - \tau_0)$.[13] If the critical stress for operating the dislocation source in different grains is about the same and is equal to τ_0, the critical condition for meso-yielding is:

$$n_i(\tau_{myi} - \tau_0) = k_{ni}\,(\tau_{myi} - \tau_0)^2\,d = k\tau_0 \qquad \text{(Eq 6)}$$

where k is a proportional coefficient; τ_{myi} is the critical shear stress for meso-yielding around the internal grain.

The internal fatigue limit, σ_{wi}, is actually τ_{myi}, expressed in the form of normal stress. Then

$$\sigma_{wi} = \sigma_0 + k_i\,d^{-1/2} \qquad \text{(Eq 7)}$$

where $\sigma_0 = 2\tau_0$ and

$$k_i = (k\tau_0/k_{ni})^{1/2} \qquad \text{(Eq 8)}$$

Eq 2-8 are suitable for the meso-yielding around an internal grain. The meso-yielding processes around a grain being located at the surface are somewhat different from those around an internal grain (Fig. 5a and b). The external surface of surface grain is free, then, the operation of the dislocation source is only restricted from the side of internal grains. Then Eq 3 should be substituted by:

$$\tau_0 = \tau - \tau_d \qquad \text{(Eq 3}'\text{)}$$

and Eq 4-8 should be substituted by Eq 4′-8′, respectively:

$$n_s = k_{ns}\,(\tau - \tau_0)d \qquad \text{(Eq 4}'\text{)}$$

$$n_s(\tau_{mys} - \tau_0) = k_{ns}\,(\tau_{mys} - \tau_0)^2\,d = k\tau_0 \qquad \text{(Eq 5}'\text{)}$$

$$\sigma_{ws} = \sigma_0 + k_s d^{-1/2} \quad \text{(Eq 6')}$$

$$k_{ns} = 2\pi (1-\nu) d/Gb = 2\, k_{ni} \quad \text{(Eq 7')}$$

$$k_s = (k\tau_0/k_{ni})^{1/2} = k_i/\sqrt{2} \quad \text{(Eq 8')}$$

The meaning of the symbols in Eq 4′-8′ is similar to that of symbols in Eq 4-8, but the footnote of "$_s$" reflects the meso-yielding around the surface grain. In Eq 6 and 6′, the critical stress for dislocation motion within grain σ_0 is small, so the ratio of o_{wi}/σ_{ws} is a value near, but less than √2. This value tallies well to the determined result (1.38) in this work. Note that similar data have been obtained for many other metals.[5-10] The obtained ratios o_{wi}/σ_{ws} are values between 1.35-1.40.

3.4 Fatigue Crack Source Position and Apparent Fatigue Limit

According to the micro-meso-process theory for fatigue crack source formation and the concept of internal and surface fatigue limit, all results in this work, as well as the mechanism for improvement of apparent fatigue limit for shot-peened specimen with internal fatigue source, can be clearly understood. For un-hardened specimen, the dislocation motion in grains at the surface or near the surface is free from the surface side and restricted only from the surrounding grains on their internal side; then, the meso-yielding always prefers to occur in the surface layer and, as shown in Fig. 3, the change of $\Delta\beta$ on unhardened specimen mainly occurs at the surface. The apparent fatigue limit in this case is actually the surface fatigue limit of metal. For the shot-peened specimen, the surface layer is hardened and the unhardened matrix metal beneath the hardened layer becomes a weaker "link." The meso-yielding zone prefers to occur in the interior. Then, the narrowing effect of $\Delta\beta$ occurs in the internal region and the fatigue crack source will be formed there (Fig. 4). In this case, the apparent fatigue limit should be quantitatively related to the internal fatigue limit of matrix metal, which is higher than its surface fatigue limit for about 1.35-1.40 times.

This mechanism for improvement of apparent fatigue limit of shot-peened specimens is different from, but not contrary to the generally accepted mechanism, according to which the improvement of apparent fatigue limit of shot-peened metallic parts is directly attributed to the decrease of mean stress of the applied stress cycle due to the induced compressive residual stress. Actually, the latter mechanism should be effective when the surface layer has not been hardened enough during shot peening and the fatigue crack source of specimen still locates at the surface. In this case, the apparent fatigue limit should be related to the surface fatigue limit of metal as well as the compressive residual stress in the surface layer.

4. Conclusions

1. The three-point fatigue limit (for 1×10^7 cycles at stress ratio of 0.05) for quenched and tempered 40CrNi2Si2Mo2V steel is 1115 MPa and rises to 1490 MPa after shot peening. The increment of apparent fatigue limit caused by shot peening is about 34%.
2. The fatigue source is at the surface for un-peened specimen; for the shot-peened specimen, it locates beneath the hardened layer, where the residual stress is tensile.
3. The "internal fatigue limit" of 40CrNi2Si2Mo2V steel, σ_{wi}, for shot-peened specimen under the nominal stress equal to its apparent fatigue limit is 1544 MPa, about 1.38 times the surface fatigue limit of the same metal, σ_{ws}.
4. The fatigue source transfers from the surface to the interior and the σ_{wi} of metal is higher than its σ_{ws} are two reasons for the improvement of apparent fatigue limit of shot-peened specimens.
5. Narrowing effects of integral width of x-ray diffraction line for crystal plane (211), $\Delta\beta$, which reflects the cyclic meso-yielding of metal during fatigue testing, have been observed in both shot-peened and un-peened specimens tested under stress levels equal to their apparent fatigue limits. Such meso-yielding zone locates at the surface for un-peened specimen with depth about 13 times original austenite grains; for shot-peened specimen, it locates beneath the hardened layer, in the region with tensile residual stress, with thickness about 12 times the original austenite grain.

References

1. K. Iida and K. Tosha: "Fatigue Strength of Work Softening Layer Produced by Shot Peening" in *Proc. 3rd Int. Conf. on Shot Peening,* Garmisch-Partenkichen (FRG), Oct. 1987, pp. 611-18.
2. Hu Nai-Sai and Zhou Huijiu: "The Effect of Surface Plastic Deformation on Fatigue Strength and Its Mechanism" in *Proc. 1st Int. Conf. on Shot Peening,* A. Niku-Lari and S.T. Al-Hassan, ed., Paris, France, Sept. 1981, pp. 351-57.
3. K. Naito, T. Ochi, T. Takahasi, and N. Suzuki: "Effect of Shot Peening on the Fatigue Strength of Carburized Steels" in *Proc. 4th International Conf. on Shot Peening,* Tokyo, Japan, Oct. 1990, pp. 519-26.
4. K. Ogawa, H. Yamada, K. Saruki, M. Yokoi, and M. Inuzuka: "Influence of Residual Stress on Fatigue Strength of Carburized and Shot Peened Notched Specimens" in *Proc. 4th Int. Conf. on Shot Peening,* Tokyo, Japan, Oct. 1990, pp. 445-54.
5. Li Jinkui and Yao Mei: "Tensile Residual Stress Field Induced by Shot Peening and Internal Fatigue Limit of Materials," *Acta Aeronaut. Astronaut. Sin,* 1990, *A11*, pp. 369-77 (in Chinese).
6. Yao Mei, Wang Shengping, and Li Jingqui: "Analysis on Fatigue Strength of Surface-Hardened Parts and Internal Fatigue Limit of Materials," *Acta Metall. Sin.,* 1993, *A29,* pp. 511-19 (in Chinese).
7. Wang Renzhi, Yao Mei, Wang Shengping, and Shao Peige: "Micro-Meso- Processes for Fatigue Crack Initiation and Theory of Internal Fatigue Limit," *Trans. Metal Heat Treatment,* 1995, pp. 26-34 (in Chinese).
8. Shao Peige, Wang Shengping, Yao Mei, and Wang Renzhi: "Influence of Carbonitriding and Afterward Shot Peening on Fatigue Limit of Low-carbon Steel," *Trans. Metal Heat Treatment,* 1996, *17*, pp. 1-6 (in Chinese).
9. Shao Peige, Wang Shengping, Yao Mei, and Wang Renzhi: "Mesoscopical Effects for Fatigue Crack Initiation," *Chin. J. Mater. Res.,* 1997, *11,* pp. 191-97 (in Chinese).
10. Wang Shengping, Yao Mei, and Wang Renzhi: "Compressive Residual Stress Introduced by Shot Peening," *J. Mater. Proc. Technol.,* 1998, *73*, pp. 57-60.
11. Zhang Ding-Quan and He Jia-Wen: "Residual Stress Analysis by X-Ray Diffraction and Its Functions," Xi'an Jiaotong University Press, Xi'an, 1999, pp. 66-73 (in Chinese).
12. G.E. Dieter: *Mechanical Metallurgy,* 2nd ed., McGraw-Hill, Inc., 1976, pp. 411-12.
13. E.O. Hall: *Yield Point Phenomena in Metals,* Plenum Publishing Company, New York, NY, 1970.