Research Progress in Effect of Metal Surface Nanocrystallization on Fatigue Property

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Abstract. Nano grains have unique structure and properties. Surface self nano technology can introduce nano structure into the surface of materials. By changing the surface structure and microstructure of metal materials, the comprehensive properties of metal materials are improved. Moreover, the surface properties of metal materials are affected by the nano grain layer, work hardening and residual compressive stress. It has unique advantages in improving fatigue performance by inhibiting the initiation and propagation of fatigue cracks. In this paper, the research progress of surface self nano technology and the change of microstructure and mechanical properties caused by it are introduced. Finally, the research progress of its influence on the fatigue properties of metal materials is emphatically reported.

1. Introduction
Nano materials refer to materials with crystal size and particle size less than 100 nanometers, which have nano effect. Nano materials have many outstanding properties for their unique structural characteristics. For example, it has excellent physical and chemical properties and mechanical properties, so it has been widely concerned and studied. It is generally believed that nano size greatly improves the strength, wear resistance, corrosion resistance and good plasticity of the material. Generally, in engineering, improving the surface properties of materials can improve the overall service performance of materials. Therefore, nano technology and surface modification technology are combined to prepare materials with nano surface layer. In addition, in the introduction of nano gradient structure, the residual compressive stress and work hardening also have obvious changes between the nano surface and the matrix. There is no obvious boundary between the surface nano layer and the matrix. Most engineering materials are very sensitive to the surface structure and properties of materials. A large number of studies have shown that nano surface can improve the fatigue properties of materials. The main work to improve the fatigue performance is to improve the overall performance of the material surface, and to effectively suppress the crack initiation and propagation stage. All kinds of excellent properties of nanocrystalline surface provide the basis for its good fatigue performance.

2. Preparation of surface nano layer
At present, the preparation methods of surface nano layer are: surface coating or deposition, Surface nanocrystallization (SNC), Surface nanocrystallization and combination of surface coating or deposition. SNC is a surface modification technology, which is a new concept put forward by Lu et al [1] in 1999. The SNC has the advantages of simple operation and low cost, and there is no obvious interface, no
separation and peeling off in the gradient change of the prepared nano layer. Other strengthening factors such as residual compressive stress and work hardening can be introduced. So, it can be the mainstream method of preparing surface nano layer. At present, the popular SNC technology as follow: Ultrasonic shot peening (USP), surface severe plastic deformation (S^2PD), Ultrasonic impact treatment (UIT), surface nanocrystallization and hardening (SNH), surface mechanical attrition treatment (SMAT), surface mechanical grinding treatment (SMGT), surface mechanical rolling treatment (SMRT), etc. The SNC method is to produce large plastic deformation on the surface and sub surface of the metal material by high-strength impact or rolling treatment on the surface of the material, so that a large number of defects are produced on the surface crystal, and finally the grains are gradually refined into nanocrystals, and the grain size gradient is generated along the depth direction. In addition, the surface impact can refine the grain, produce residual stress and work hardening layer on the surface. Li et al. [2] used surface mechanical grinding treatment (SMGT) technology to create gradient structure in the surface layer. The grain size increased from nanometer level to submicron level and micron level, and the thickness of gradient layer obtained was much larger than that of SMAT. Fig. 1 is a schematic diagram of SMGT processing. The cylindrical sample rotates at a certain speed with respect to the hemispherical WC / Co tool tip (radius R), which slides from V2 to the right along the rod axis. When the tip enters a certain depth of the specimen in advance (α_p), plastic deformation area will be generated under the tip, as shown in Fig. 1b. a small part of the accumulation at the tip may flow upward along the circular tip and may be removed in the form of fragments, while most of the accumulation is compressed downward by the tip to form a deformed surface layer.

**Figure 1.** Schematic illustrations of (a) the SMGT set-up and (b) the plastic deformation layer induced by the tool tip.

3. Microstructure of SNC

In the process of preparing surface nanostructures, the plastic deformation and refinement of the surface layer grains are caused by the plastic deformation of the surface. The study of the refinement process and results plays an important role in the follow-up research process.

Y. samih et al. [3] deeply analyzed the microstructure of SMAT, divided the area after SMAT treatment into three areas, and measured the thickness of each area: (I) the nanocrystalline area, the ultra-fine grain area with a large submicron size, which is the final stage of grain refinement, with a thickness of about 26.5 μ M. (II) the transition zone where the initial micro grains are broken under large deformation. The transition zone extends down to a depth of about 50 μ m, with a thickness of about
23.5 μM. This zone is where the grains are broken due to severe deformation but fail to reach the range of ultra-fine grains. (III) The deformation zone of simple plastic deformation of initial grains, which is 50-183 μm away from the surface and 133 μm thick, is characterized by the continuous decrease of dislocation density. It is also considered that the formation of twin and dislocation array in SMAT process results in grain breaking, and then submicron grains are formed, and the advancing degree of refinement process obviously depends on the local strain of the material. Sara et al. [4] used high-strength shot peening to treat low alloy steel (39NiCrMo3, UNI EN 10083). The experiment shows that obvious nano grains with large angle grain boundary and random orientation can be seen on the surface of the material after treatment, and the surface can obtain significant residual stress after treatment. At the same time, the surface roughness is improved. Yang et al. [5] used the Ultrasonic Impact Treatment (UIT) method to get gradient nanocrystalline structure on the surface of AISI 304 stainless steel, and researched the microstructure of processed samples. After treatment, three typical areas were observed: gradient nanocrystalline layer area, severe plastic deformation zone area and coarse-grained area (small deformation zone). It shows that the grain size increases with the increase of depth. The content of martensite in the surface layer increased after treatment.

In addition, in the study of grain refinement, it is known that the grain refinement mechanism of materials with different stacking fault energy (SFE) is not the same. For materials with high SFE, the grain refinement is mainly controlled by dislocation activity, including the generation of high dislocation density, the formation of sub grains and the evolution of sub grains to high dislocation orientation [6]. For materials with low SFE, the grain refinement is mainly due to the formation of twin and the subsequent twin twin cross formation of finer grains [7] or the interaction between twin and dislocation in twin substrate layer [8].

4. Work hardening and residual compressive stress
It is known in the research that some additional factors, such as the change of work hardening layer, residual compressive stress and surface roughness, will be introduced in the process of introducing nano gradients, among which work hardening and residual compressive stress have been proved to have a significant impact on the fatigue performance.

Wang et al. [9] used ultrasonic surface rolling processing (USRP) to treat 40Cr. It was found that the surface hardness of the treated samples increased by 52.6% compared with the original samples. The increase of hardness is attributed to grain refinement and work hardening. After treatment, the grain size increases along the depth direction gradually, while the hardness decreases. Chang. Ye et al. [10] investigated the influence of ultrasonic nano crystal surface modification (UNSM) on the residual stress, microstructure change and mechanical properties of austenitic stainless steel. It was found that the surface hardness increased to 7 GPa. The results show that nano grains, high volume fraction martensite and high dislocation density are helpful to improve the hardness. With the increase of the distance from the treated surface, the hardness decreased rapidly. It is found that there is a significant residual compressive stress in the surface layer of the nanostructure of SMRT samples, and the residual compressive stress reaches to ~ 1400MPa in the top layer, and decreases with the increase of the surface depth of the processed samples. Lei et al. [11] studied the change of fatigue properties of AISI 316L stainless steel treated with SMAT, and found that the surface microhardness gradually decreased from the maximum value (~ 4.2GPa) of the surface to the matrix value (~ 1.5GPa) with the increase of the depth. The yield strength of CG sample is ~ 212MPa while that of SMRT sample is ~ 289MPa, and the ultimate strength is ~ 606MPa to ~ 641MPa. It is found that the residual stress on the surface after SMAT reaches ~ 1400MPa, and gradually decreases towards the depth. After 9 × 103 cycles, the surface residual stress is relaxed to ~ 230MPa. Leon L. Shaw [12] et al. Studied the influence of surface severe plastic deformation (S²PD) and shot peening (SP) on the fatigue performance of C-2000 superalloy. It was found that both S²PD and SP can produce work hardening layer on the surface of the sample, and the surface hardness of the original sample has greatly improved, and the work hardening layer thickness produced by SP is 200 mm, while S²p D is 800mm. The results show that the maximum residual stress
of s2pd (1020MPa) is about 18% higher than that of SP (860MPa), and the maximum residual stress of the two treatments is on the sub surface rather than the surface.

5. Effect on fatigue performance

In the process of preparation, the microstructure, physicochemical properties and mechanical properties of the surface nano layer have changed a lot. It makes the material with nano surface layer have different performance from the common coarse-grained material in fatigue test. Nano surface changes the microstructure of the material surface, and serious plastic deformation introduces residual stress and work hardening to the material surface, which will have a huge impact on the crack initiation and propagation.

H.W. Huang [13] et al. Prepared gradient nanostructure surface layer on AISI 316L stainless steel by SMRT and researched its fatigue behavior. The results show that under high cycle fatigue, the fatigue limit of SMRT treated sample is 78% higher than that of coarse-grained sample, and 33% ~ 50% higher under low cycle fatigue. It is found that for coarse-grained materials, the cracks originate on the surface, propagate to the interior and cause fracture. However, after SMRT treatment, cracks appear on the sub surface and propagate to the surface and the interior, resulting in instant fracture. The reason is that the nano surface layer restrains the localization of strain and makes the plastic deformation more uniform.

Feng et al. [14] used SMGT technology to prepare gradient structure on coarse-grained pure iron substrate, and studied its high cycle fatigue performance. It was found that SMGT improved the Fatigue resistance of the material, and the surface nano gradient structure increased the fatigue strength of the material from 182MPa to 252MPa, and found that under the high stress amplitude, the fatigue crack initiated on the surface as in the coarse-grained material. However, when the stress amplitude is low, the fatigue life increases and the position of initiation changes to the inside of the gradient layer. It is considered that in the surface gradient structure, the blocking stress of dislocation is very large, which makes the crack not easy to sprout on the surface under the lower stress amplitude. Wang et al. [15] researched the influence of the surface gradient structure formed by SMGT technology on the crack growth behavior of medium carbon steel s38c, and found that the gradient structure of nano surface layer makes the stress distribution at the crack tip more uniform, and the local plastic deformation area at the tip is smaller than that of coarse-grained material. The results show that the gradient structure of nano surface layer can inhibit the crack growth. At the same time, the stress distribution and the local plastic deformation area of the crack tip under the gradient structure with residual stress are studied. Compared with the gradient structure, the effect of adding residual stress on crack growth is enhanced.

Li et al. [16] calculated the dislocation distribution at the crack tip in theory, and studied the influence of nano grain size gradient on dislocation distribution and crack growth. It is considered that the gradient structure can increase the emission dislocation at the crack tip, reduce the stress concentration at the crack tip, passivate the crack and reduce the crack growth. Therefore, the material with nano grain gradient has high strength and good fracture resistance. Zhang K et al. [17] studied the influence of surface crack suppression on the fatigue performance of bearing steel by surface gradient nanostructure. It was considered that the residual stress of bearing steel after SMRT treatment reduced the surface defects. Under the cyclic stress amplitude of 900MPa, the life of SMRT sample increased by at least two orders of magnitude compared with that of the original sample. It is suggested that the improvement of fatigue properties and the inhibition of surface mode fracture of SMRT may be related to the decrease of initial stress intensity factor [18, 19], which is mainly due to its high strength and structural uniformity. It is found that the residual stress also reduces the stress intensity factor and improves the fatigue performance. Yang et al. [20] used the Navarro Rios (N-R) model to research the influence of the surface grain size and the grain size gradient along the depth caused by the surface nanocrystallization (SNC) on the fatigue damage of metal materials. The results show that the grain growth rate is proportional to the grain size. The smaller the grain is, the longer the fatigue life is. It is considered that the introduction of more obstacles (grain boundary, sub grain boundary, dislocation tangle (DTS), dense dislocation wall (DDWS), etc.) in the process of short crack growth by surface nanocrystallization (SNC), which will hinder the crack growth. In addition, it is found that the growth rate of short crack decreases with the
decrease of the surface grain size and the grain size gradient along the depth, which indicates that the surface nanocrystallization (SNC) can effectively improve the fatigue life of metal materials. D. Li et al. [21] used SMAT technology to prepare the surface nano layer of SS400 carbon steel plate, and gave the curve of the relationship between the fatigue life n and the stress amplitude s after SMAT treatment and the original sample. It was found that the fatigue life of the sample after SMAT treatment was significantly longer than that of the original sample under the low cycle fatigue and high cycle fatigue conditions. When the stress amplitude is 320 MPa, the fatigue life of the sample after SMAT is more than 5 times of the original sample. When the fatigue life is $5 \times 10^6$ cycles, the fatigue strength of SS400 steel is increased by 13.1% by SMAT process. They believe that the improvement of fatigue properties of SS400 steel is due to the combined effects of compressive residual stress, work hardening subsurface and nanostructure surface layer. T. Roland et al. [22] studied the effect of the surface layer of nanocrystalline after SMAT treatment on the fatigue properties of 316L stainless steel. The results show that the life of the treated samples is greatly improved and the fatigue strength is increased in both high cycle and low cycle fatigue cycles. The results show that the increase of nanocrystalline layer, martensite content and residual compressive stress have different contributions to the improvement of fatigue properties. It is found that after annealing, the residual compressive stress on the surface is relaxed, but the fatigue life in the sample is improved. And they think that the relaxation behavior caused by heat treatment can be described by the self-diffusion activation energy of dislocation climbing and annihilation. T. Trš Ko et al. [23] carried out severe shot peening (SSP) on 50CrMo4 steel, and studied its influence on the fatigue performance of the sample under the ultra-high cycle fatigue cycle. The results show that the fatigue life of the treated samples is increased by 23%, but the increase is not obvious under high cycle. They think that severe shot peening (SSP) will form high residual compressive stress on the surface of the material, and in the category of ultra-high cycle fatigue, the residual compressive stress is the main influencing factor.

6. Research trend

The nanostructures on the metal surface show a series of different characteristics from the common coarse-grained materials, which provides a new research idea for the study of new materials and new processing technology. By using these unique characteristics of surface nanostructures, the comprehensive performance of materials can be greatly improved. SNC technology enables the surface nanostructure to be realized in most metal materials and widely used. Through SNC, the material surface can have high strength, hardness and wear resistance. Strengthening the surface layer of metal materials, while maintaining the original properties of the core, has a huge impact on the initiation and propagation of material cracks. Nowadays, the research on the fatigue properties of metal materials mainly focuses on the inhibition of crack initiation and the delay of crack growth. Most studies have found that after SNC treatment, the fatigue strength and fatigue life of materials have been improved under low cycle and high cycle fatigue, but the specific fracture mechanism of fatigue fracture needs to be further studied, and most of the research focuses on low cycle and high cycle fatigue, and the research on the effect of surface nano on the fatigue performance of materials under ultra-high cycle fatigue is still in progress. At the same time, it is found that the introduction of nano grains, work hardening and residual compressive stress in the surface nanocrystallization (SNC) have different contributions to the improvement of fatigue performance, but the contribution of single factor to the improvement of fatigue performance has not been fully studied. In addition, nano surface treatment can also cause the change of surface roughness, which is generally considered to be harmful to fatigue life. Therefore, the research on the influence of surface nano technology on the fatigue properties of metal materials needs to be further studied.

7. Epilogue

The treatment cost of surface nano technology is low and the technology is simple. The fatigue life of metal materials has always been the focus of attention. With the increase of fatigue life, the cost will be
greatly reduced. The excellent comprehensive properties of metal materials brought by surface nanostructures bring a new scheme for improving the fatigue life of materials.

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