Technical Paper

High Strength and Compactness of Gears by WHSP (Double Hard Shot Peening) Technology

Satoki Matsumura

Naoji Hamasaka

Shot peening is one technique used to enhance the fatigue strength of gears and springs. There have been, however, many uncertain aspects of the relationship between hardness and residual stress distribution provided by shot peening on one hand and the fatigue strength that can be derived from them on the other. Improving the conventional shot peening method, a two-stage peening technology (Double Hard Shot Peening [WHSP] technology) has been developed, whereby fine shot balls less than 0.1 mm in diameter are blasted, in addition to peening by shot balls of 0.8 mm in diameter as at present. The new technology provides high hardness and compressive residual stress directly below the surfaces of the gears, thereby, significantly improving their fatigue strengths.

This paper reports on the WHSP technology and application examples of the same.

Key Words: *gear, shot peening, fatigue strength, lightening weight and miniaturization, residual stress*

1. Introduction

Recently, the needs for high output, long life, and lightening weight of automobiles and construction machinery is constantly increasing, necessitating further increases in loads to gears and drive system parts. To meet this trend, further enhancement of the strengths of the individual parts is demanded. In response to these demands, a variety of attempts have been made in two aspects—new material development and process improvement. Among these attempts, the effects of shot peening have been validated in conspicuously enhancing fatigue strength, and shot peening has started to be used widely. The shot peening method of blasting shots onto parts by jetting them from a nozzle by accelerating them especially using high-pressure air or high-pressure water jet features high energy of shot balls compared with the conventional shot peening method using revolution jetting by impellers (**Fig. 1**). At the same time, the new shot peening method provides stronger plastic processing onto the surfaces of parts, supplying a high compressive residual stress. [1), 2)]

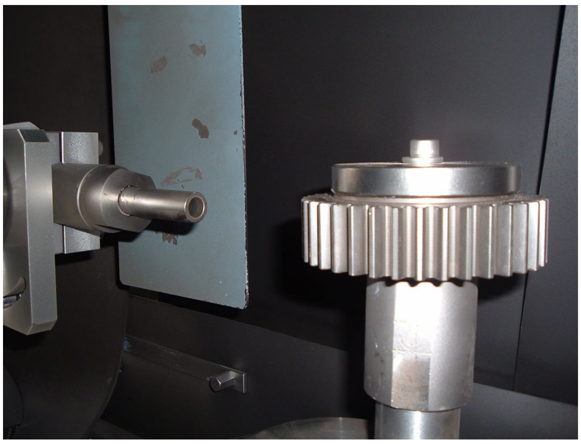


Fig. 1 Shot peening through air nozzle

The compressive residual stress provided on the surfaces of processed parts by the crash of shot balls is considered to be the main principle explaining why fatigue strength is enhanced by shot peening. The level of residual stress provided on surfaces vary in accordance with the processing conditions (hardness, grain size, and blasting pressure and time of shot balls), and the fatigue strength enhancement rate varies accordingly.

This paper reports the Double Hard Shot Peening (WHSP) technique that has been developed by modifying the conventional shot peening method and that has succeeded in dramatically enhancing the fatigue strength of gears compared with before.

2. Fatigue Breaking of Gear

Dedendum bending fatigue of the gears is caused by fine cracks that generate near the dedenda by a repetitive load applied to the dedenda, resulting in final rupture (breaking). **Figure 2** shows an SEM image of a ruptured surface. Judging from the condition of the ruptured surface, the process of bending fatigue rupture can be classified into the following three stages:

Stage 1: Fine cracks generate.
Stage 2: The cracks expand and spread.
Stage 3: The cracks rapidly open up and develop into final rupture.

The factors dominating each of the foregoing stages in fatigue rupture and the level of contribution of these factors need be defined to further enhance the fatigue strengths of gears. A schematic depiction of the dedendum bending fatigue of the gears is illustrated in **Fig. 3**. [3), 4)]

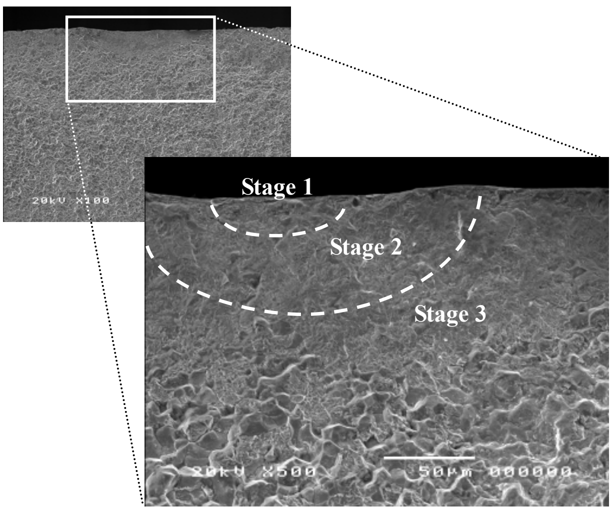


Fig. 2 SEM photographs of a surface of a gear ruptured by bending fatigue

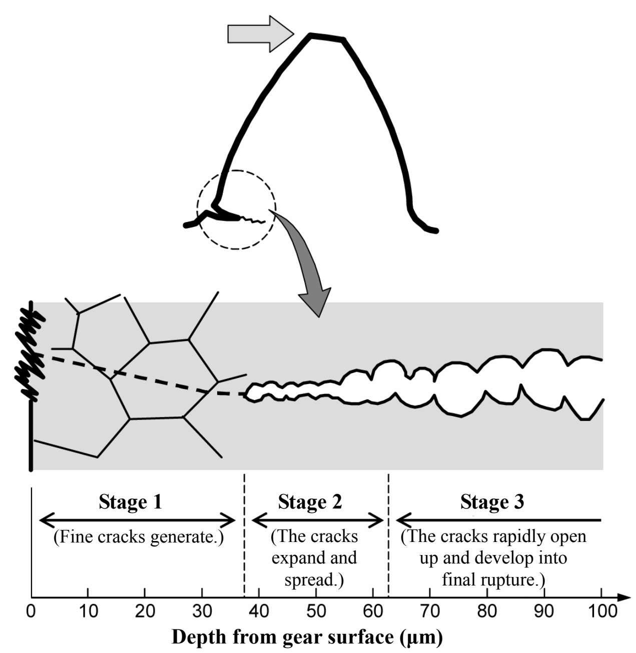
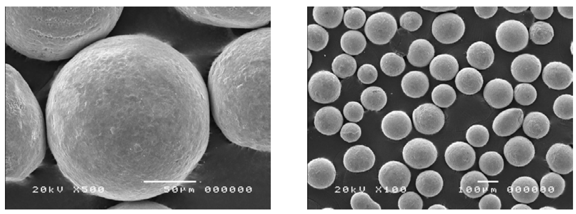


Fig. 3 Schematic depiction of dedendum bending fatigue of the gear

3. What is WHSP?

Shot peening technology was industrialized in the 1940s aimed at strengthening springs and is not a new technology. Nevertheless, the technology is now widely used to drastically enhance the dedendum bending fatigue strength of gears spurred by the social demands mentioned above. In the past, steel balls (hardness HRc60) of 0.6 to 0.8 mm in diameter shown in **Fig. 4 (a)** were mainly used in shot peening technology, principally to provide a compressive residual stress from the surfaces of parts to relatively deep portions. WHSP is intended to provide a compressive residual stress to shallower portions that are nearest to the surfaces of the parts by peening fine steel balls of 0.1 mm in diameter (**Fig. 4 (b)**) in addition to shot peening steel balls of larger diameters.



(a) ϕ 0.8mm (b) ϕ 0.1mm

Fig. 4 Shot steel balls

The residual stress distributions in the tooth bottoms of a gear that are shot peened by conventional shot peening (shot ball diameter of 0.8 mm) and by fine shot balls (diameter of 0.1 mm) are shown in **Fig. 5**. The graph shows that conventional shot peening produces a residual stress distribution at a depth of about 50 μm, peaking to about -1000 MPa. A study of the schematic depiction of fatigue bending in **Fig. 3** indicates that conventional shot peening curbs Stage 2 (cracks expanding and spreading) in the fatigue rupture process. Shot peening with fine shot balls produces residual stress distribution in very shallow portions of a depth of about 20 μm peaking to -1200 MPa or more, indicating that shot peening of fine balls curbs Stage 1 (generation of fine cracks).

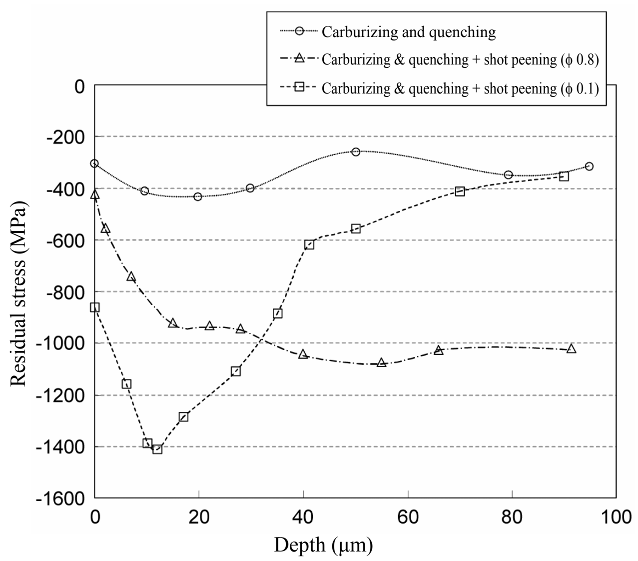


Fig. 5 Differences in residual stress distribution by shot balls - 1

Based on this, a dedendum bending fatigue test of single gears was conducted. The test results are shown in **Fig. 6**, indicating that shot peening of fine shot balls of 0.1 mm in diameter produces a higher fatigue strength (about 1.25 times) compared with shot peening with balls of 0.8 mm in diameter. This finding shows that Stage 1 (generation of fine cracks) is a more dominant factor than Stage 2 (cracks expanding and spreading) in the fatigue rupture process of the bending fatigue strength of gears. In other words, provisioning of a compressive residual stress to surface-layer portions that are the nearest to the surface by blasting fine

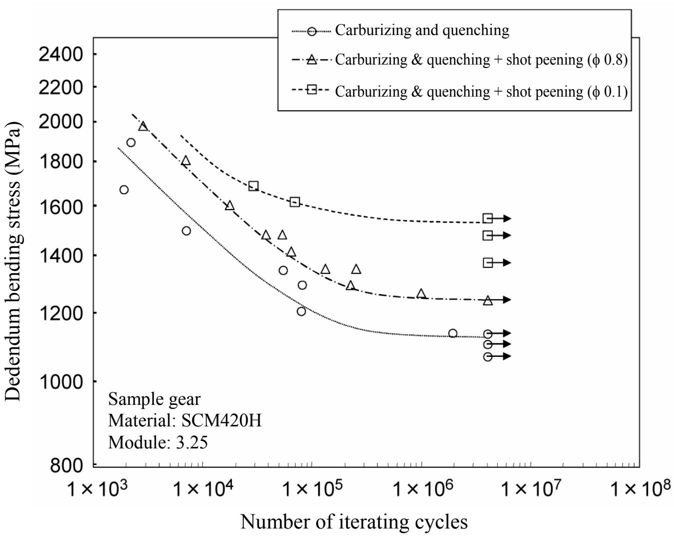


Fig. 6 Results of dedendum bending fatigue test - 1

shot balls is more effective in enhancing the dedendum bending fatigue strength than providing a compressive residual stress to deep portions by large shot balls.

Studying these results, a gear was processed by shot-peening 0.8-mm balls in Process 1 and shot-peening 0.1-mm balls in Process 2 as shown in **Fig. 7** to curb both the generation of fatigue cracks and the expansion and spreading of cracks, to dramatically enhance the bending fatigue strength of the gears. Shot peening of Processes 1 and 2 produced the residual stress distribution shown in **Fig. 8**. The graph indicates that a high compressive residual stress can be provided to portions deeper than 50 μm, as well as to portions that are nearest to the surface, succeeding in achieving a thick compressive residual stress layer. WHSP gears

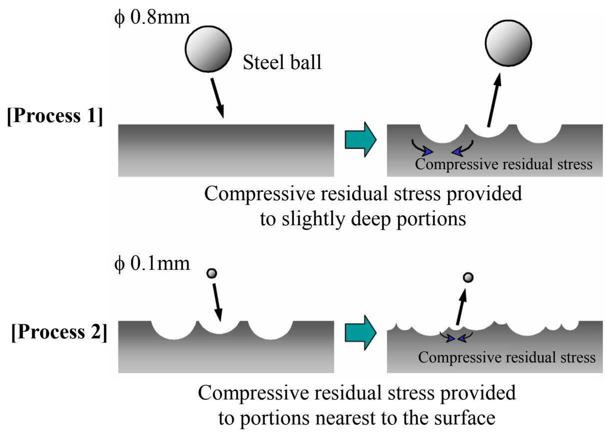


Fig. 7 Schematic diagram of WHSP

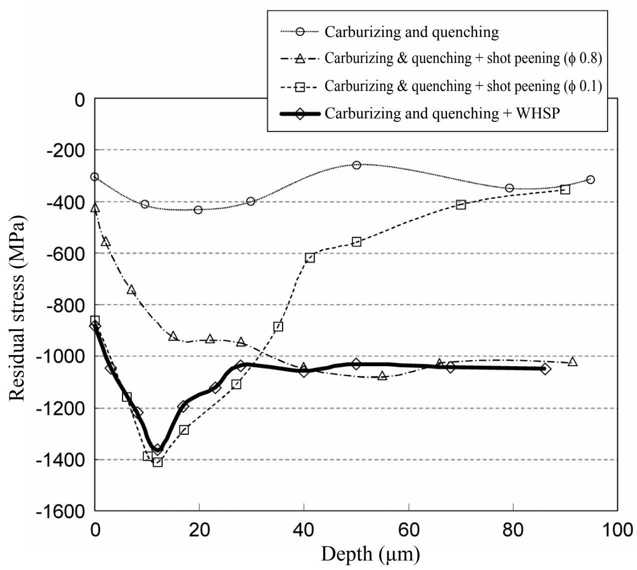
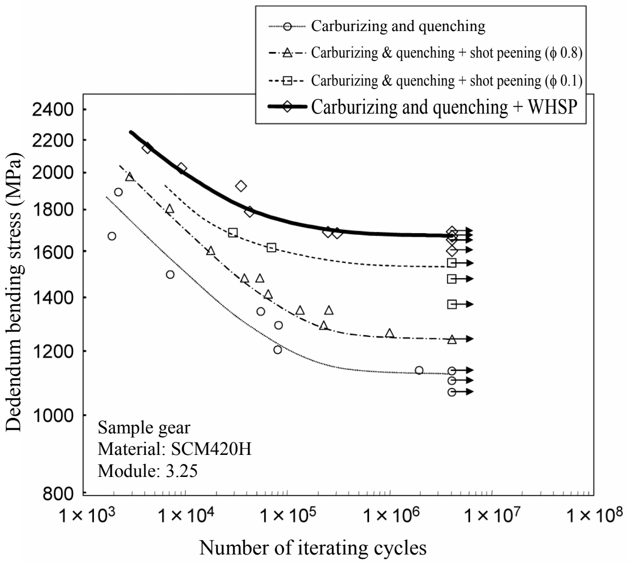


Fig. 8 Differences in residual stress distribution by shot balls - 2

featuring this residual stress distribution were similarly tested for dedendum bending fatigue. The test verified that the bending fatigue strength increased 1.35 times compared with conventional shot peening (**Fig. 9**).



[Comparison of dedendum bending fatigue strength]

Carburizing and quenching	1.00
Carburizing & quenching + shot peening (ϕ 0.8)	1.10
Carburizing & quenching + shot peening (ϕ 0.1)	1.38
Carburizing and quenching + WHSP	1.49

Fig. 9 Results of dedendum bending fatigue test - 2

4. Process Assurance

Thus viewed, shot peening like WHSP that uses fine shot balls processes portions nearest to the surfaces of parts. Application of this technology to high-volume production will therefore require quality management up to the previous process as an important requirement. For example, gears that are carburized and quenched sometimes form a soft layer called a "slack quenching layer" as illustrated in **Fig. 10**. Oxides are formed on the surfaces of parts, which are carburized and quenched, through reaction between a very small amount of O_2 in the atmospheric gas and alloy elements such as Cr, Mn, and Si. The portions near the surface tend to become tissues such as troostite and bainite due to deterioration in the hardenability caused by deletion of alloy elements in the matrix through the generation of oxides. The hardness of these tissues is low compared with that of quenched martensite. These tissues do not become strain-induced martens tic tissues even after strong processing such as shot peening. A compressive residual stress can hardly be provided. **Figure 11** shows the relationship between the depth of a slack quenching layer and dedendum bending fatigue strength. The diagram shows that the dedendum bending fatigue strength is not prominent if the slack quenching layer is limited to a certain depth, but that lowering of fatigue strength becomes prominent if a slack quenching layer is formed on the surface deeper than the depth, exhibiting no effects in enhancing the bending fatigue strength by shot peening or by WHSP. As mentioned above, this attests that quality of heat treatment in the previous process is an important management item for WHSP.

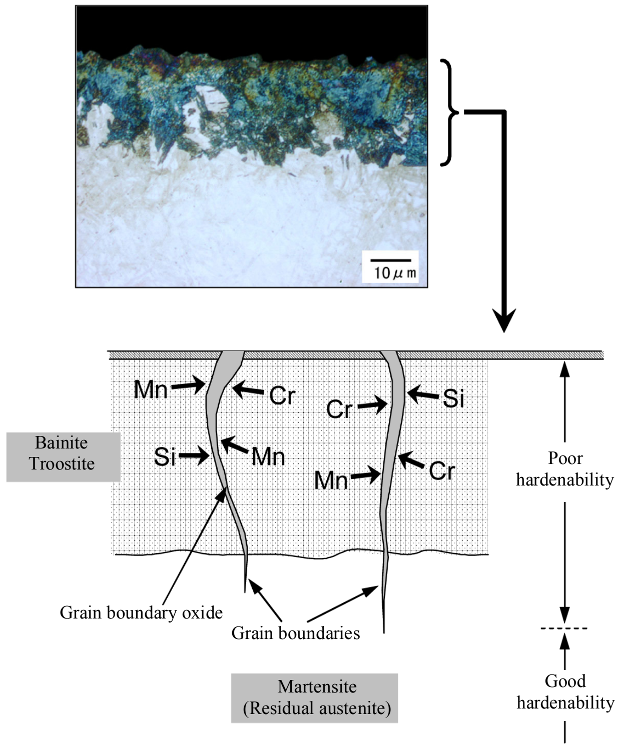


Fig. 10 Slack quenching tissue

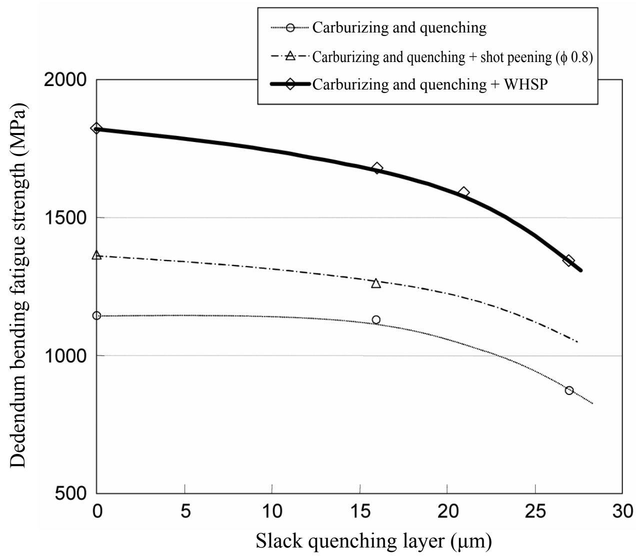


Fig. 11 Correlations between depth slack quenching layer and dedendum bending fatigue strength

5. Application Examples

The primary purpose in using shot peening with gears, shafts, and other parts is the enhancement of the strength and reliability of the systems and equipment that house them. At Komatsu, too, shot peening is mostly used to enhance the strength of gears, followed by miniaturizing gear speed reducers. **Figure 12** illustrates the structure of a final speed reducer of hydraulic excavators. Generally speaking, speed reducers and transmission systems are mostly gears and shaft parts that transmit motive power and the castings and forging parts that contain them as carriers or housings. The dimensions and weights of the entire system are more often than not determined by the gears and other parts that are contained in them. Downsizing commensurate with the high strength of gears, shafts, and other parts can also downsize their peripheral parts as a synergetic effect, thereby allowing a significant reduction in the weight of an entire system. The example of speed reducer shown in **Fig. 12** accomplished downsizing of a system by applying the WHSP technology mainly to the gears. As a result, the total weight of the system could be reduced by about 5%. Needless to say, problems such as enhancement of the durability of bearings and clutch disks must be solved in parallel aside from gears. As a core technology, WHSP will undoubtedly be used widely in the future.

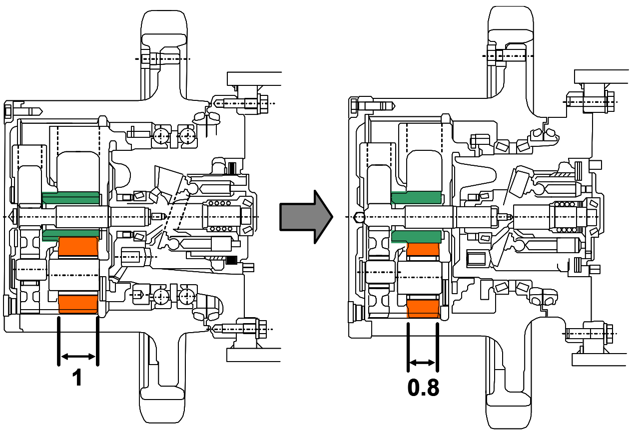


Fig. 12 Example of application of WHSP

6. Conclusion

Emphasis was placed on first accomplishing a strong peening strength in the early stage of the shot peening technology of an air nozzle type. At present, emphasis seems to be placed instead on peening under appropriate conditions while paying attention to portions that produce cracks, to the quality of processed parts, and to other aspects. Shot peening has been verified to be effective with parts that are carburized and quenched and with parts that are treated by other methods and is also effective in improving bending fatigue strength. Shot peening will be used in various other applications. The quality of parts to be treated is also important and greatly affects their strength. Shot peening will be used more widely as its peripheral technologies improve such as heat treatment and material technologies, including reinforcement of grain boundaries and no abnormal carburizing layers.

References

1) Katsuji Tosha, "Surface Integrity by Shot Peening," Journal of Japan Society for Abrasive Technology, Vol. 47 No. 3 (2003)
2) Naoji Hamasaka, "Current Status and Future View of Hard Shot Peening Technology," Netsu Shori, Vol. 39 No. 5 (1999)
3) Masahiko Mitsubayashi, Hideo Aihara and Ryuji Miyata, "Phenomenon Analysis of Shot Peening," Society of Automotive Engineers of Japan, 1993 Academic Meeting
4) Keiji Nasu, Hidemasa Ishigami, Akira Tange and Katsuyuki Matsui, "A Consideration of the Fatigue Rupture Process and Fatigue Strength Enhancement Method," Transactions, Fatigue Symposium, 2000

Introduction of the writers

Satoki Matsumura

Entered Komatsu in 2001.
Currently assigned to the Manufacturing Engineering Development Center, Corporate Production Division.

Naoji Hamasaka

Entered Komatsu in 1979.
Currently assigned to the Manufacturing Engineering Development Center, Corporate Production Division.

[A few words from the writers]

The research process and results obtained in the application of the shot peening technology to actual machines provided useful knowledge. This technology will be one of the key technologies suiting the current needs for lightening and downsizing of parts required by the automobile and construction machinery industries. Future plans include feeding back of information obtained in the past and expansion in application to other machine models.