Fine Particle Bombarding Technology and Functional Development of Metal Surface

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ABSTRACT
   Recent trends toward weight reduction, energy saving, and higher-efficiency of automobiles and aircrafts compared with previous generations mean that structural materials with improved and diversified functionality are in great demand. Materials are required with higher fatigue and wear resistance, greater toughness, better sliding properties and other characteristics combined. Incorporating these characteristics together in a material requires putting different functions in the material that may be contradictory to each other. Thus far, there has been no material in existence possessing all these functions at one time. It can be expected, however, that modifying the material surface to give a functional gradient to the superficial layer will give rise to a high-value-added material that meets required diversified characteristics. This paper reports on the features of fine particle bombarding technology developed by paying attention to the high-speed bombardment of metallic and non-metallic fine particles, the fatigue characteristics of fine particle-bombarded springs, and some examples of metallic film formation.

KEY WORDS
   Fine particle bombarding, fatigue strength, flat wire spring, microstructure, valve spring, TEM, dry surface coating, nitriding, titanium oxide film, tin coating.

1. INTRODUCTION
  Commonly, due to mechanical and chemical surface damage, the surface layer quality of the machine elements and structural parts can become deteriorated and the effective cross sectional area can be decreased as well, resulting in fractures. Therefore, a variety of surface treatment methods strategies are in practical use to modify the surface of those elements and parts to achieve high performance with properties such as wear and fatigue resistance (C. Kagaya and T. Morita, 2003).
  With the current increased demand for improvement in energy and natural resources consumption, surface quality, and cost reduction, a surface modification technology using high velocity impact phenomena of fine particles, or a fine particle bombarding process: FPB, has attracted the attention from numerous industrial fields (C. Kagaya, 2006).

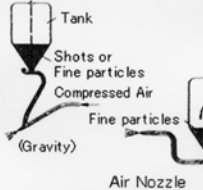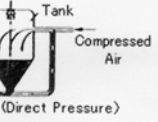## 2. The features of fine particle bombarding technology
   FPB is an excellent and high-utility surface modification technology developed in Japan (K. Mase, Y. Miyasaka, 1990). As shown in Table 1, this technology accelerates metallic or non-metallic fine particles with the aid of an air nozzle jet system, and has them bombard a material surface to improve the functionality of the collided surface and its vicinity. The features of the technology include: The remarkably small size of particles used, compared with those of normal shot peening; the very high collision speed of the particles; the notably small size of arc-height; and the high plastic strain induced in the surface layer of treated workpieces. In other words, in the FPB process using fine

particles with high hardness such as cast steel (750 HV), high-speed steel (1000 HV) or ceramics (1000 HV), fine craters with a plastic deformation layer below the surface are formed on the material surface. In consequence, high compressive residual stress, strain hardening and transformation can occur.

When using soft metal fine particles such as tin (15 HV), titanium (190 HV), or other metals in FPB process, such fine particles collide and coalesce, forming a metallic film on the surface of the workpiece. A workpiece which has acquired such particular surface film characteristics can be utilized as a machine element with a special function.

Thus FPB processes improve fatigue, wear and pitting resistance, sliding property, and/or other characteristics to a great extent. The effect of the FPB distinctively reveals itself in combination with heat treatment, carburizing or nitriding, and especially at a notch where stress concentrates. Fig. 1 shows the principal uses of fine particles and their scanning electron microscopic photos.

Table 1. Comparison of FPB with other representative methods

|		Conventional Shot Peening	Hard Shot Peening	Fine Particle Bombarding
Ejection Type		Impeller	(Gravity)	Air Nozzle (Direct Pressure)
Shots or Fine Particles	Material	Steel(Cut wire), Cast Iron, Cast Steel, Glass		Steel, High Speed Steel, Ceramics
	Diameter	0.3～2.8mm		0.01～0.1 mm
	Hardness	430～480HV	560～700HV	750～1000HV
	Velocity	30～70m/s	90～100m/s	150～200m/s
Arc-Height		under 0.5mmA	0.6～1.0mmA	0.01～0.1 mmA
Surface Hardening		Work Hardening	Work Hardening・Transformation	
Peak Point of Compressive Residual Stress		Subsurface		Surface or Near Surface
Surface Roughness		Large～Medium		Small
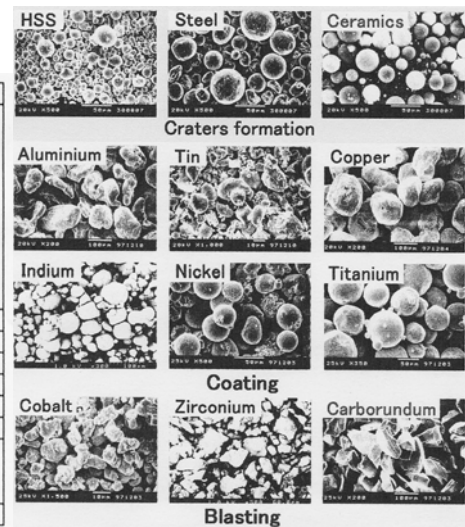
Fig. 1. Principal uses and SEM photos of fine particles

3. Effect of shot-particle size on fatigue strength of high strength springs

Development and application of the FPB process to springs was carried out at Suncall Co. (patented in the USA and other countries). Flat spring steel wire (valve-spring quality chrome silicon spring steel) was supplied, with a thickness of 0.97 mm and a width of 5.1mm. This material had heavily deformed fine pearlite microstructure. Wave springs cold-formed from the supplied flat spring wire and then stress-relief-tempered were shot-peened with steel particles of different nominal diameters (50, 100, 200 and 300 μm). Fatigue strengths at 10^6 stress cycles obtained are schematically shown in Fig. 2. The springs FPB processed with steel particles of 50 μm nominal diameters were found to have the highest fatigue strength among the various wave springs that were shot-peened. The hatched area on the figure indicates that the fatigue strength changes with the velocity of particles used (65 to 210 m/sec). It is noted that the bombardment velocity of the nominal particle size 50 μm (at which the highest fatigue strength was
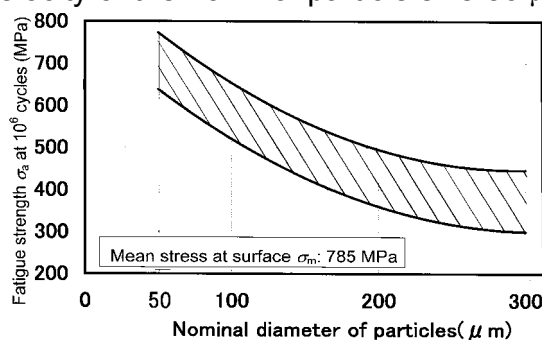

Fig. 2. Effect of shot diameter on fatigue strength of flat wire spring (wave spring)

obtained) was slower than the maximum velocity tested.

In the surface layer (from the surface to about 3 μm below surface) of the FPB processed wave springs, most of the cementite (Fe_3C) lamellae had disappeared, in contrast to the as-rolled flat wire and as-conventionally shot-peened wire, according to transmission electron microscopy: TEM, as shown in Figures. 3 and 4.
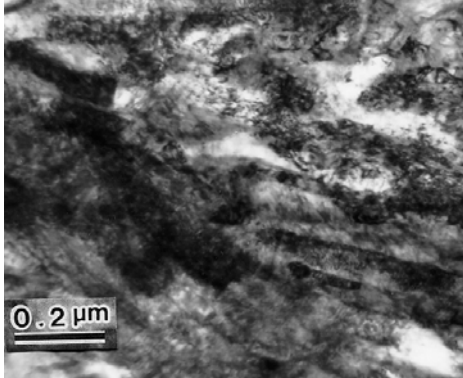

Fig. 3. TEM image of FPB processed flat wire. Depth from surface: ~2 μm

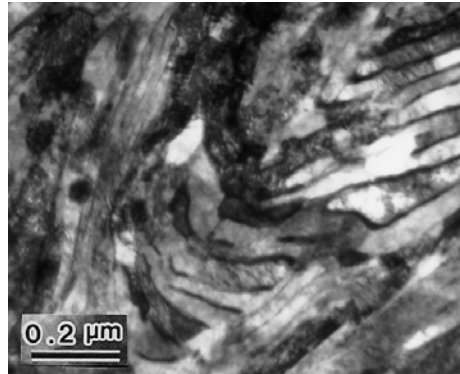Fig. 4. TEM image of flat wire conventionally shot-peened with 0.3 mm diameter steel shots. Depth from surface: ~1.3 μm

X-ray diffraction analysis with Cu Kα X-ray also indicated no diffraction peaks from cementite in the FPB processed wire surface, although cementite diffraction peaks were observed for the as-rolled wire surface (Y. Yamada et al, 2000). Carbon solubility in steel depends not only on temperature but also on the dislocation density in the matrix ferrite. In other words, because the carbon atoms can have a lower free energy when they are segregated around the dislocation core in ferrite than they have in cementite precipitates, multiplication of dislocations in ferrite due to plastic deformation causes cementite dissolution until the completion of the segregation of carbon atoms around dislocations, when the cementite dissolution velocity is high enough at an elevated temperature (Y. Yamada 1974, 1976). D. V. Wilson (1957) suggested that the capable dissolution of cementite occurs in deformed steel as follows; when deformed steel is aged at an elevated temperature, cementite can dissolve to an appreciable extent to supply carbon for the new dislocations. Y. Yamada (1974, 1976) termed this kind of age-hardening as a second stage of aging for cold-drawn high carbon steel wire. According to Yamada, the cementite dissolution velocity is a function of temperature, time and cementite morphology (T. Fujita, Y. Yamada, H. Kawakami, 1973).

In the case of fine lamellar cementite, it actually starts to dissolve in ferrite at ~120 to150 °C and above (See Table 2), and the dissolution is accelerated with temperature. On the contrary, it hardly dissolves at all below 100 °C. Furthermore, strong plastic

Table 2. Time necessary to start dissolution of cementite

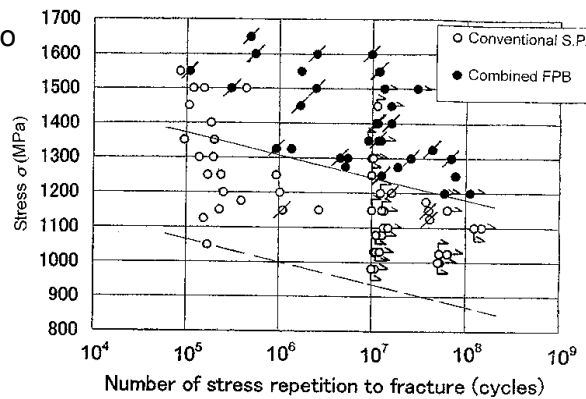| Temperature ℃	Time sec
100	7,000
140	320
180	20-30
220	1.5
260	0.2
300	0.04
340	0.008
380	0.002
420	0.0007

Fig. 5. Rotary bending fatigue test results for high strength OT wires with a diameter of 3.2 mm.

deformation and the following aging at warm temperature (second stage), carried out repeatedly, was found to continue dissolving the cementite successively and increasing the carbon content in matrix ferrite in high carbon steel (Y. Yamada, 1975 and 1977). In the FPB process, plastic deformation that takes place repeatedly with repeated impact of fine steel particles on the target steel surface causes repeated dislocation multiplication and heat generation, realizing the repetition of deformation and strain aging described above.

The aforementioned fact that the cementite lamellae had mostly vanished in the FPB processed flat spring steel surface layer, indicates that the surface layer attained a certain elevated temperature such as 300 °C or above, at which temperature cementite dissolution progressed with sufficient rapidity during the FPB process.

According to Hutchings, ~80 % of the kinetic energy of a spherical particle impacting with flat target metal, is converted to heat that raises the temperature of the surface layer of the target metal indented by contact with the spherical particle, as a result of the friction between the spherical particle and impacted target metal and the plastic deformation in the indented target surface layer (I. M. Hutchings, 1983). Together with Bowden and Tabor (1954) he also indicated that the loading time, the time at which the sphere comes to rest after it started to contact the target surface, is proportional to the particle diameter. As a result, they indicated that the mean plastic strain rate during loading time is inversely proportional to the impacted particle diameter. Total average strain in the target surface layer impacted by a sphere is a function of a/r, where a is the chordal radius of indentation, and r is bombarded particle radius (I. M. Hutchings, 1983). When the particle velocity is the same, this a/r value is not considered to be markedly different for steel spheres with different diameters. From these considerations, the smaller the bombarding particle is, the shorter the loading time is. For smaller particle bombardment, the heat generation due to friction and plastic deformation around the impacted target surface layer is more adiabatic, making the rapid transfer of such local heat by thermal conduction toward the target inner portion more difficult. As a result, therefore, the greatest temperature increase is realized   at the impacted spring steel wire surface layer in the case of the smallest particle bombarding.

4. Effect of the combined FPB process on the fatigue properties of spring wire and springs

The effect of the final FPB process in combination with other surface modification technologies on valve spring wires and valve springs for automobile engines was investigated using 3.2 mm diameter high strength oil-tempered (OT) wire for valve springs with a tensile strength of 2091 MPa and the chemical composition; 0.58C, 1.49Si, 0.70Mn, 0.29Ni, 0.84Cr, 0.07V, plus a small amount of impurities and balance Fe (in mass%).

At first, the effect of the FPB process following conventional shot-peening (with 0.6mm diameter cut-steel-wires with 550 HV at the velocity of 73 m/sec) was investigated using the OT wires cut into pieces. All the specimen wires were conventionally shot-peened. About half of them were then FPB-processed with 50 μm diameter steel particles. These specimens were fatigue tested with Nakamura type rotary bending fatigue test machines. Fig. 5 shows the results, where the slashed symbols indicate the fractures which originated from sub-surface non-metallic inclusions and those with no slash indicate the fractures which started from the wire surface. The combined FPB process was found to be effective in fatigue fracture prevention both from the wire surface and from inclusions (Yamada et al, 2000).

Using the same grade of OT wire, cold-formed helical springs were made basically as follows: Stress relief temper at 420   , descaling, gas-nitriding at 430   for 3 hours, conventional shot-peening using the 0.6 mm diameter cut-steel-wires (73m/sec) and

finally the FPB process. The spring fatigue test results are plotted in Fig. 6. According to Satoh et al (1995), the same springs described as above except that only the final FPB process was omitted, had a fatigue strength of 588± 549 MPa when read on the S-N diagram. This fatigue strength at 5 X 10^7 cycles is considered to be equivalent to 686± 529 MPa, because the rise of the mean stress by $\Delta\tau_m$ is equivalent to a drop in stress amplitude level of 1/5 $\Delta\tau_m$. Comparing the fatigue strengths of these two kinds of nitrided springs, the nitrided springs treated with the combined FPB process have significantly
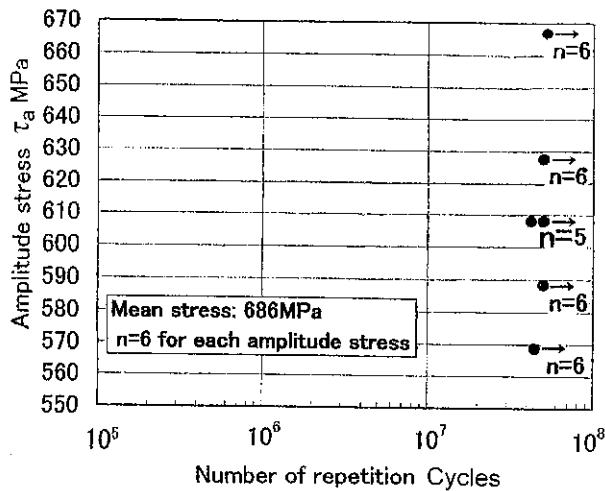

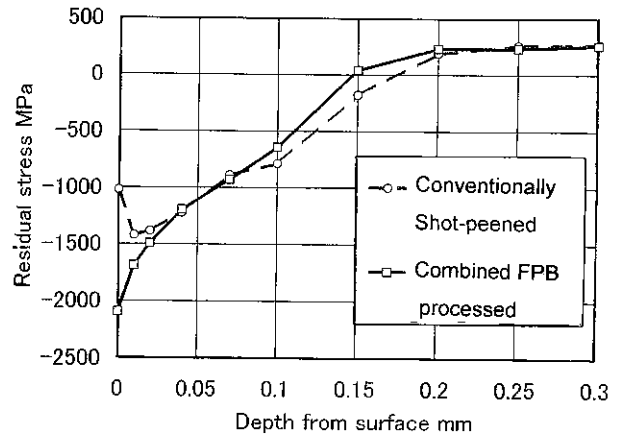Fig. 6. S-N plots for gas-nitrided, conventionally shot-peened and then FPB processed springs

Fig. 7. Residual stress distributions of nitrided valve springs

higher fatigue strength than the nitrided springs conventionally shot-peened (Y. Yamada et al, 2002). The nitrided springs tested had a Vickers hardness of ~850HV at the surface layer, which is greater than the 0.6 mm diameter cut-steel-wires (hardness: 550HV) and comparable to or less than the fine steel particles used (850 – 910HV) in the FPB process. The nitrided springs treated with the combined FPB process, had a surface residual stress of –2100 MPa in contrast to that of –1000 MPa for conventionally shot-peened nitrided springs (Fig. 7). This very high compressive residual stress without harmful surface defects at the spring surface is considered to be the main reason why high fatigue strength was obtained in the FPB processed springs.

5. Forming a metallic dry film

In FPB treatment, the high-speed collision of fine particles to a material surface not only raises the material surface temperature (H. Maeda, N. Egami, C. Kagaya et al, 2001), but also generates heat in the particles themselves, which increases their own temperature, and thus soft or low-melting point metal particles such as tin, titanium, indium or copper can readily form metallic dry films on the material surface.

Fig. 8 presents examples of formed metallic films (C. Kagaya, 2006). When tin particles are jetted at a rate of 150 m/s or higher, the surface of a steel plate, as shown in Fig. 8(a), is uniformly covered with a tin film. The film thickness is approx. 1 to 2 μm.

Fig. 8. Examples of metallic film formation
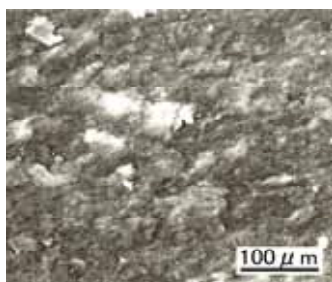
(a) Tin film   (b) Titanium film

The tin film exhibits strong adhesion to the substrate, and is therefore highly effective in reducing sliding resistance. The fine tin particle bombardment locally to a portion of a steel part is also effective in preventing the tin film coated portion from being nitrided in salt-bath nitriding or gas soft-nitriding, because the tin film is stable at a nitriding temperature of 580°C.

Figure 8(b) shows titanium-coated ceramic balls (Φ8 mm diameter). When this ceramic ball is bombarded by fine titanium particles, heat is generated, forming a titania film, which acts as a photo catalyst. Titania film is attracting attention as an environmentally friendly material, as it is able to purify air, water and oil, deodorize, and be antimicrobial. It is hoped that the superior characteristics of those films will be utilized in numerous applications including improved lubrication of metallic films, increased wear and corrosion resistance.

6. Conclusions

This paper described the features of the FPB technology, related technical trends, and future perspectives. This technology is useful in developing high-functional materials or high-value-added products economically by modifying the surface.

The technology is expected to have a wide range of applications.

REFERENCES
F. T. Bowden, D. Tabor: The Friction and Lubrication of Solids, Oxford, 1954
T. Fujita, Y. Yamada, H. Kawakami: Aging of high carbon steel wire in drawing and its prevention, Kobe Steel R & D, Vol. 23, No. 3, 1973, pp.44-52 (in Japanese)
I. M. Hutchings: The behaviour of metals under ballistic impact at sub-ordinance velocities, Material Behavior under High Stress and Ultrahigh Loading Rates, 1983, New York Plenum Press, p.p.161-195
C. Kagaya: Development Trends and Technical Outlooks of Fine Particle Peening (FPB), Journal of the Japan Society for Precision Engineering, Vol.72, No.9 (2006), pp.1067-1070
C. Kagaya. T. Morita: Fatigue Properties of Surface-Modified Materials, Journal of the Society of Materials Science Japan, Vol.52, No.5 (2003), pp.546-551
H. Maeda, N. Egami, C. Kagaya et al: Analysis of Particle Velocity and Temperature Distribution of Struck Surface in Fine Particle Peening, Transactions of Japan Society of Mechanical Engineers, Series C, Vol.67, No.660 (2001), pp.2700-2706..
K. Mase. Y. Miyasaka: Method of Surface thermo-mechanical treatment for metal-product, Japan Patent, No.1594395 (1990).
H. Satoh, Y. Kawaguchi, M. Nakamura et al: Influence of surface flaw on fatigue life of valve springs, Wire J. International, March 1995, p.p.120-125
D. V. Wilson: Effects of plastic deformation on carbide precipitation in steel, Acta Met. Vol.5, 1957, p.p.293-302
Y. Yamada: Static Strain Aging of Eutectoid Carbon Steel Wires, Tetsu to Hagane, Vol. 60, No. 12, 1974, pp.1624-1638 (in Japanese) or Transaction of The Iron and Steel Institute of Japan, Vol.16, 1976, p.p.417-426 (In English)
Y. Yamada: Effect of Pre-Aging Treatment on the Strain Aging Characteristics of Hard Drawn Eutectoid Carbon Steel Wire, Tetsu to Hagane, Vol. 61, 1975, p.119 (in Japnese)
Y. Yamada: Strain aging of high carbon steel wires, 3rd International Conference on Drawing, Ostrava, Czekoslovakia, Sept., 1977
Y. Yamada, T. Saitoh, M. Ishida et al: SAE Technical Paper Series 2000-01-0791,2000
Y. Yamada, K. Teratoko, T. Saitoh et al.: Improvement of Fatigue Strength of Nitrided High-Strength Valve Springs by Application of a New Super Fine Shot-Peening Technology, SAE 2001 Transactions, Journal of Materials and Manufacturing, Section 5, Vol.110, September 2002, pp.729-737