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Atsumi Hatano and Kunio Namiki
Daido Steel Co., Ltd.

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ABSTRACT

Although shot peening is an old technology, it has been revived in the Japanese automotive industry as a means to enhance the fatigue durability of steel components. Particular emphasis is on the application of "hard shot peening". "Hard shot peening" is a high intensity peening technology which results in a higher magnitude of compressive residual stress and, therefore, greater fatigue resistance than conventional shot peening.

The first area of development was in high performance carburizing steels suitable for hard shot peening. Desirable traits were enhanced by reducing the carburizing anomalies resulting from intergranular oxidation and by the enhancing case toughness. Further improvement of fatigue resistance has been accomplished by dual peening, first with hard shot followed by smaller diameter steel shot at a lower intensity.

This paper also describes the development of long life shot media for hard shot peening.

THE DEVELOPMENT of high fuel efficiency vehicles is an urgent need in the automotive industry, especially with CAFE regulations becoming stricter. One approach is to reduce the weight of automotive parts to achieve greater fuel economy. To achieve this, two methods are effective; the application of lighter materials and the downsizing the parts by strengthening of the steels used.

There are many techniques to obtain higher strength such as alloying, the application of clean steels, high quality heat treatment, and introducing residual stress by shot peening. Among these methods, shot peening is gaining increased use as one of the most cost effective ways to enhance fatigue durability.

Shot peening is a cold working process performed by projecting hard particles onto the surface of parts which results in residual stress[1]-[3]*. Even though it is an old technology, new developments are occurring in "hard shot peening".

"Hard shot peening" is defined as a high intensity peening with an arc height larger than 0.6mmA and using hard shot media such as HV550 or higher. It is well known that hard shot peening provides high compressive residual stress in a thin surface layer and results in remarkably high fatigue strengths[4]-[6].

In spite of its benefits, there remains several problems to be solved in hard shot peening. The surface of a workpiece becomes roughened[7] and the life of the shot media decreases. This paper will present a study on high performance carburizing gear steel suitable for hard peening, shot peening technologies to obtain higher fatigue strength and long life shot media.

APPLICATION OF HARD SHOT PEENING

NEW STEELS FOR HARD SHOT PEENING-Although shot peening is beneficial, it is important to reconsider the materials being peened to obtain a higher fatigue strength. The surface of a part becomes roughened by the high energy projection of hard particles and the surface roughness is influenced by the material being peened. This roughening is accelerated by the existence of carburizing anomalies. Intergranular oxidation is one of these defects which occurs at prior austenite grain boundaries during the carburizing process with an endothermic atmosphere. It depletes oxide forming alloying elements adjacent to the grain boundary, which results in a local decrease in the hardenability and promotes the forming of soft transformation products on quenching. Because they are oxide formers, silicon, manganese and chromium are also hardenability increasing elements.

Another disadvantage of hard shot peening, the decrease in toughness of peened parts, is caused by the decomposition of retained austen-

*Numbers in parentheses designate references at end of paper.

ite to martensite and work-hardening. It is inevitable as long as conventional carburizing steels are used.

It is, therefore, important to select the optimum carburizing steel in the application of hard shot peening. High performance gear steel, DSG1, is one of the candidates. The fundamental properties of DSG1 have already been published[8][9]. The chemical composition of DSG1 is shown in Table 1. This steel is characterized by decreased intergranular oxidation and soft transformation products by reducing its silicon content to less than 0.15%. Furthermore, case toughness is improved by reducing the grain boundary embrittling element phosphorus and by increasing the molybdenum content up to 0.4%.

Table 1 Chemical composition of DSG1 steel (wt.%)

Steel	C	Si	Mn	P	S	Ni	Cr	Mo
DSG1	0.20	<0.15	0.70	<0.015	0.015	-	1.00	0.40

MECHANICAL PROPERTIES OF DSG1

EXPERIMENTAL PROCEDURES- The chemical compositions of DSG1 and JIS SCM420 are shown in Table 2. SCM420, the most popular carburizing steel in Japan and equivalent to SAE4118, was used for comparison. Two tons of DSG1 was melted with a gas refining arc furnace and rolled into 90mm diameter bars. SCM420 was obtained as commercially produced 153mm square billet and hot forged to 90mm diameter bars. Normalizing was carried out by holding at 1193K followed by air cooling.

Test gears were machined from the 90mm bars. The details of the test spur gears are shown in Table 3. After machining, the gears were carburized and tempered. Carburizing was carried out at 1183K for 19.8ksec followed by quenching in 353K oil from 1103K. Tempering was performed at 433K for 7.2ksec. Finally, shot peening was applied with a centrifugal type peening machine with an arc height of 0.45 mmA and 0.7mmA using 0.8mm diameter cast steel shot. The former intensity is considered a normal one, and the latter is a hard one. Gear fatigue tests were carried out with a power circulated type gear fatigue tester.

Table 2 Chemical composition of test steels (wt.%)

Steel	C	Si	Mn	P	S	Ni	Cr	Mo
DSG1	0.19	0.06	0.82	0.009	0.021	0.07	1.07	0.40
SCM420	0.20	0.24	0.82	0.012	0.013	0.07	1.15	0.15

Table 3 Dimension of test gears

Dimension	Pinion	Gear
Module	2.5	2.5
Number of teeth	28	32
Pitch circle diameter(mm)	70	80
Pressure angle(deg.)	20	20

Residual stress was measured at the tooth face by X ray diffraction after cutting three teeth off to introduce the X rays. The size of the irradiation area was 2x2 mm, and the measurement was performed along the tooth trace direction.

TEST RESULTS-Figure 1 shows the tooth root fatigue properties. DSG1 exhibits a higher fatigue strength than SCM420 in as carburized condition in the whole region from the low to high cycle. For shot peened gears, although the difference between both steels was small, DSG1 still maintains its superiority. It should be noted here that the effect of shot peening is much greater than that of alloying.

Carburizing and shot peening properties of test gears are summarized in Table 4. It is indicated, generally, that with increasing peening intensity, the surface hardness and residual compressive stress increase. Retained austenite, however, decreases.

The differences are confirmed in the data for DSG1 and SCM420 as follows. DSG1 shows higher surface hardness and residual compressive stress. The amount of retained austenite in a carburized state and the decomposed austenite by shot peening for DSG1 are larger than those of SCM420. The intergranular oxidation depth, furthermore, for DSG1 is shallower than that of SCM420. When considering these factors, the superior fatigue durability of DSG1 to SCM420 is presumed to be due to higher surface hardness and the larger compressive residual stress. These are derived from an intergranular oxidation-less carburized layer. A. Ahmad et.al.[10] has indicated that shot peening after the removal of the soft transformation products results in increased surface residual compressive stress. Their study is in good agreement with this study and suggests the usefulness of DSG1.

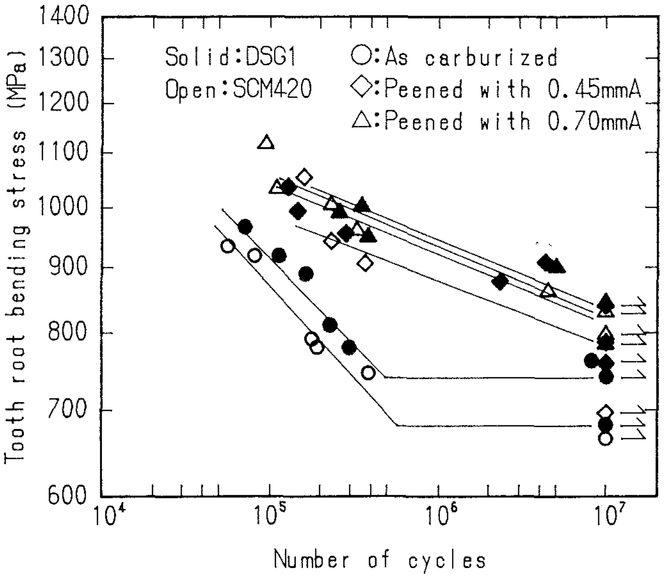

Fig.1 Gear fatigue properties of JIS SCM420 and DSG1

Table 4 Carburizing and shot peening properties of test gears

Steel	Peening intensity (mmA)	Hardness (HV)		Effective case depth (mm)	Retained austenite (%)	Inter-granular oxidation depth(μm)	Residual stress (MPa)	
		Surface	Core				surface	0.05mm depth
DSG1	-	744	340	0.95	25.8	5	-271	-285
	0.45	786	368	0.90	11.6	3	-461	-632
	0.70	810	370	0.90	8.4	3	-596	-1199
SCM420	-	720	442	1.00	18.6	15	-254	-242
	0.45	720	457	0.90	6.9	15	-353	-503
	0.70	778	438	1.15	3.1	8	-569	-1040

Furthermore, the toughness of gear steels being peened must be considered because shot peening deteriorates case toughness. The relation between shot peening intensity and Charpy impact value is demonstrated in Fig.2. Charpy impact tests were performed using carburized specimens, the notch geometry of which is 2mm depth and 10mm radius. The carburizing conditions were the same as mentioned previously.

DSG1 hard shot peened with an arc height of 0.7 mmA maintains a higher impact value than that of non-shot peened SCM420. Therefore, DSG1 is regarded as a suitable steel for hard shot peening, which results in a high fatigue strength without deteriorating its toughness.

Based on this fundamental data, DSG1 subjected to by hard shot peening has been applied to transmission gears and is contributing to the downsizing of the transmission[11].

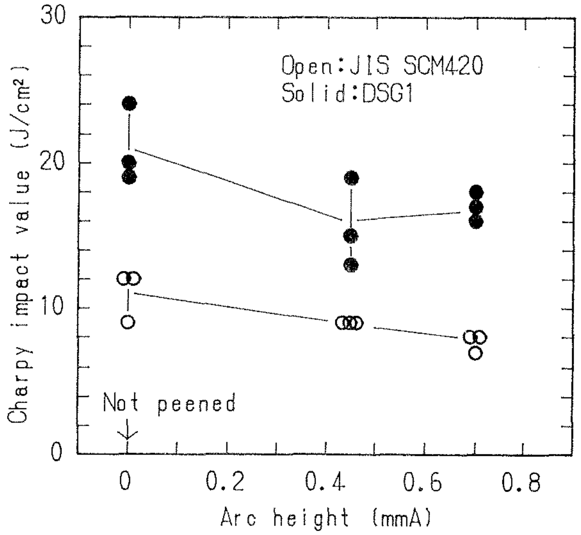

Fig.2 Relation between Charpy impact value and shot peening intensity

NEW SHOT PEENING TECHNOLOGY

PURPOSE-It is widely recognized that compressive residual stress enhances the fatigue strength in carburized components, because the propagation of a crack is arrested by residual compressive stress. In a shot peened part, the maximum value of the compressive stress is located just below the surface at a depth of about 0.05mm, and the surface value is not so high, as shown in Fig.3. To compensate for this surface compressive stress depression, additional study was carried out on beads peening. Beads peening, as defined here, is shot peening with lower intensity using a small shot media such as 0.1mm diameter shot[12].

EXPERIMENTAL PROCEDURES- At first, a gear fatigue test was carried out using test gears peened under several conditions. The test steels were JIS SCM420 and DSG1 prepared by the same process as mentioned previously. The shot peening conditions are shown in Table 5.

The conditions investigated included hard peening with hard steel shot, beads peening with smaller diameter hard shot at a lower intensity and "dual peening". "Dual peening" is a combined process, first with hard peening followed by beads peening.

Besides the fatigue test, the hardness and residual stress distributions were examined. The residual stress profile was obtained by

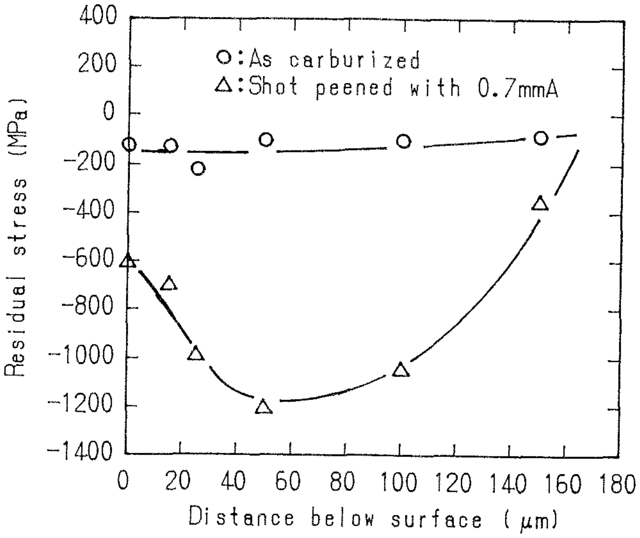

Fig.3 Effect of shot peening on residual stress profile

repeating X ray diffraction measurement and electro-polishing. Fracture surfaces were also observed with a scanning electron microscope.

Table 5 Shot peening conditions

	Shot diameter (mm)	Shot hardness (HV)	Arc height (mmA)	Peening time (sec)
Hard peening	0.8	700	1.0	90
Beads peening	0.1	800	0.05	15
Dual peening	0.8+0.1	700+800	1.0+0.05	90+15

TEST RESULTS- The hardness profiles for tooth roots of the test gears made of SCM420 are shown in Fig.4 and 5. The hard shot peened gear shows the highest surface hardness followed by the dual and beads shot peening, and non-peened gears show the lowest value. No difference was observed among these shot peening parameters for the profiles below 0.4mm deep.

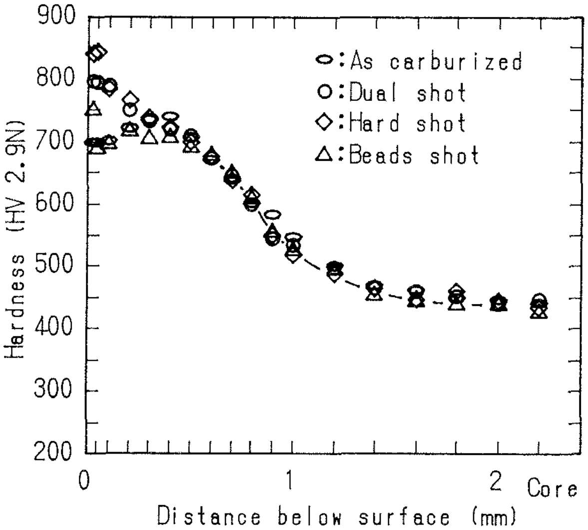

Fig.4 Hardness profiles at tooth roots

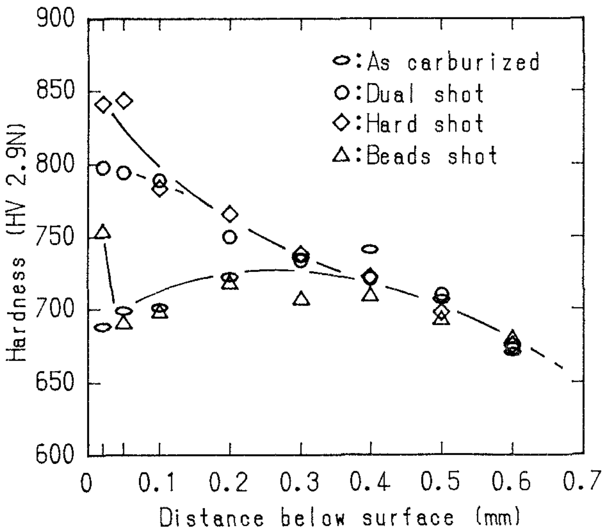

Fig.5 The details of hardness profiles adjacent to surface shown in Fig.4

Figure 6 shows the residual stress profiles. It should be pointed out that peening conditions affect the magnitude and the depth of compressive stress. The beads peened gear shows an extremely high compressive stress of 1.2 GPa at the surface, although it maintains the same profile as that of non-peened sample below 0.03mm. The dual shot peened gear is different from the hard peened one in the region just below the surface. This compressive stress increment is due to the second stage beads peening after hard peening.

Gear fatigue test results are shown in Fig.7. The dual shot peened gear exhibits the highest strength followed by hard peening, and then by beads peening. It gives a 1.5 times higher fatigue strength than a carburized one. It is noted, furthermore, that even single beads peening provides 1.2 times improvement,

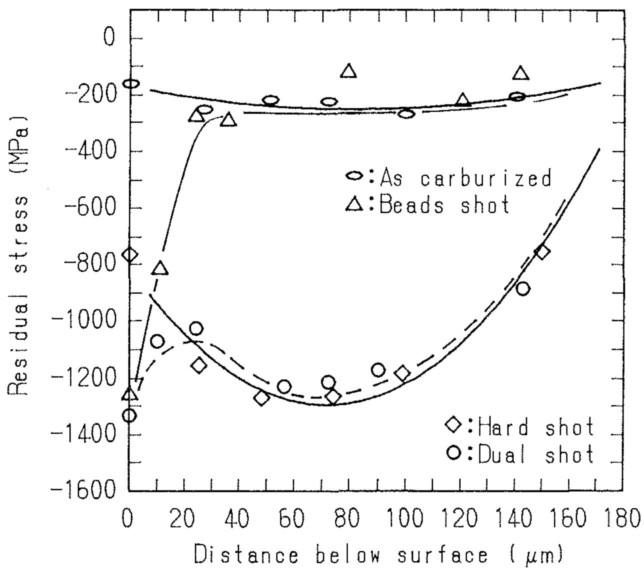

Fig.6 Residual stress profiles of SCM420

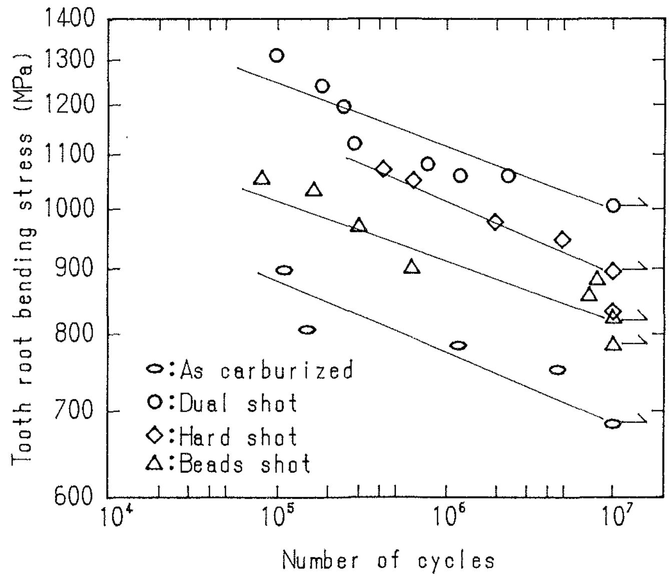

Fig.7 Gear fatigue properties of SCM420

in spite of its low peening intensity. It is generally recognized that a fatigue crack initiates only in regions of tensile stress and normally start from the surface. The large compressive stress adjacent to the surface is believed to offset the applied tensile stress and to retard fatigue crack initiation[13].

Figure 8 compares the fatigue limits for DSG1 and SCM420 shot peened with two different conditions. One is conventional shot peening using 0.8mm diameter cast steel shot with an arc height of 0.45mmA, the other is beads peening with 0.1mm diameter shot with 0.05mmA. Fatigue limit is defined as the fatigue strength at 10^7 cycles. Beads shot peening provides a higher fatigue limit than conventional peening. It is revealed, furthermore, DSG1 exhibits higher fatigue limits in both peened and non-peened conditions.

Figure 9 shows the SEM fractographs taken from the fracture origin at the tooth root of SCM420 gears. The fracture mode is composed of intergranular and transgranular ones, and no difference is observed. On the other hand, it is noteworthy that the tool marks from the hobbing cutter observed in the carburized gear become flattened by shot peening. Since the tool marks potentially can play a role as a stress raiser, the modification of the machined surface by shot peening is considered to be another cause of enhanced fatigue durability.

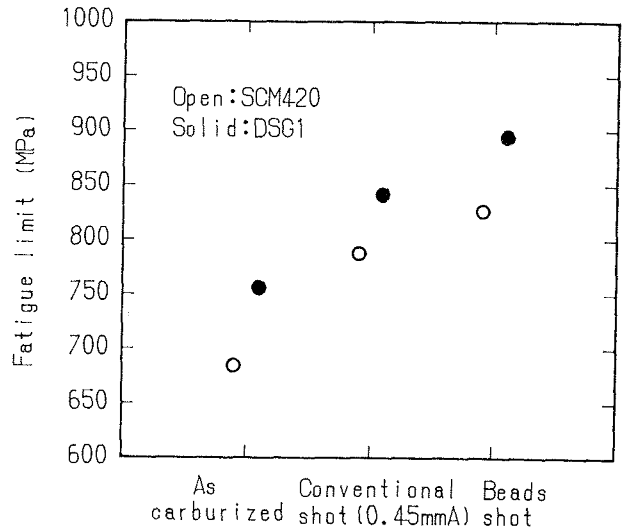

Fig.8 Comparison of gear fatigue limits

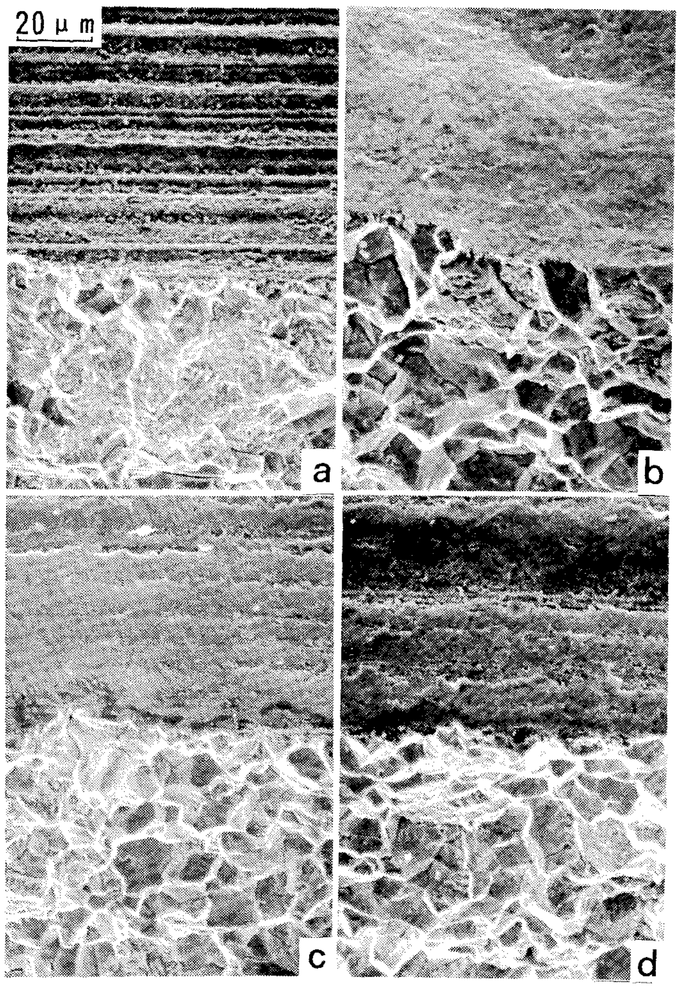

Fig.9 SEM fractographs of fatigue fractured gears (a) As carburized (b) Dual shot peening (c) Hard shot peening (d) Beads shot peening

DEVELOPMENT OF HARD AND TOUGH SHOT MEDIA

PURPOSE-The media generally used for shot peening are often small particles of cast steel or cut wire. Usually cast steel shot is used in this application, as recommended in SAE J827. The cast steel shot is produced by the water atomizing method and hardened-tempered to a hardness of HV392 to 513. Hard shot peening, however, requires hard shot media around HV700 especially for the peening of case hardened parts.

Owing to repeated projection against hard parts, shot will fracture over a period of time. Generally, the harder shot media become, the more brittle and the shorter its usable life, which results in an increase in production cost[14]. When fracturing occurs, peening intensity is also diminished due to the lower mass of broken shot[15][16]. More important, however, is the surface damage due to the impacting of these broken particles.

Based on this background, additional study was made into long life shot media suitable for the hard shot peening process.

FRACTURE MECHANISM OF CAST STEEL SHOT-First, we observed the fracture surface of the broken cast steel shot. The composition was 0.85C-1Si-1Mn, and the hardness was HV550. Figure 10 shows the SEM fractographs. The fracture surface is composed of micro void coalescence mode intiated from carbides and a dendritic cast structure. The dimple pattern obtained here is characterized by its smooth and shallow nature with little plastic deforma-

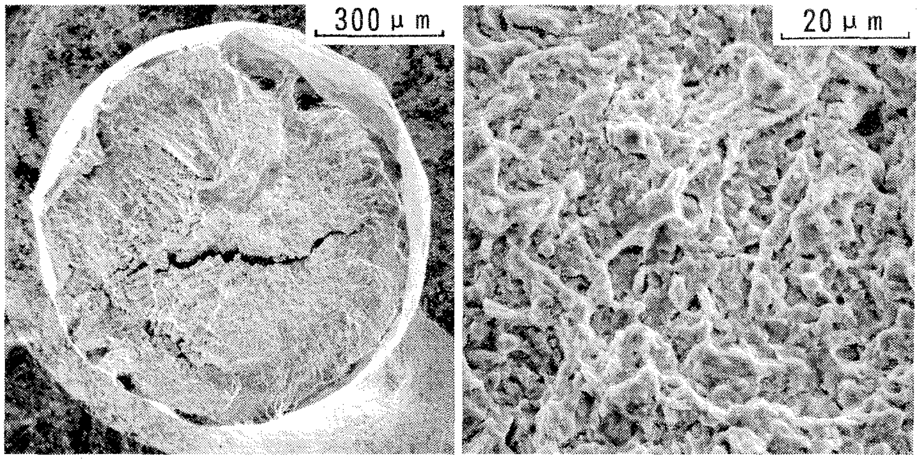

Fig.10 SEM fractographs of fractured conventional cast steel shot

tion because of the large number of carbide particles.

Next, we studied the effect of the shot hardness on the life of conventional cast steel shot by varying the tempering temperature. Ervine test results are shown in Fig.11. Initial shot size was 1.0 to 0.84mm, and broken shot was screened when broken to less than 0.71mm. It is revealed that the life decreases with an increase in hardness. This tendency is prominent at the hardnesses higher than HV600.

Based on this data, a study was made on two types of shot media with compatible high hardness and toughness. One is high toughness cast steel shot and the other is pre-conditioned high strength steel cut wire.

DESIGNING OF NEW STEEL SHOT–To obtain high toughness cast steel shot two measures were adopted. One was the reduction of carbide precipitates by decreasing the carbon content. The other was the refinement of the dendritic cast structure by applying the rapid cooling centrifugal atomizing method. In order to determine the optimum carbon content, Ervine tests were carried out using shots with carbon contents ranging from 0.4 to 1.1%. Figure 12 shows the test results. Relative life, here, is defined as the ratio of the usable life to that of normal cast steel shot containing 0.84%C.

There exists a negative corelation with the carbon content, which indicates low carbon cast steel shot is preferable to obtain long life. However, a carbon content higher than 0.5% is required to maintain the hardness of the carburized parts. Based on this data, the chemical composition of the new grade was decided on as shown in Table 6. Conventional shot, designated in SAE J827, is also listed for comparison. Beside a lower carbon content, the new grade is characterized by its lower manganese, phosphorus and sulfur contents which enhances toughness.

For the second candidate for high toughness shot, the composition of a suitable cut wire was reconsidered. The composition of the new grade for pre-conditioned cut wire is shown

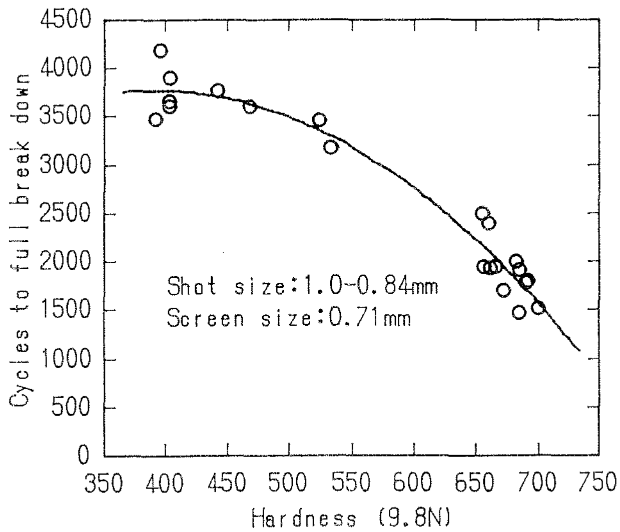

Fig.11 Life of the variable shots evaluated by Ervin test machine

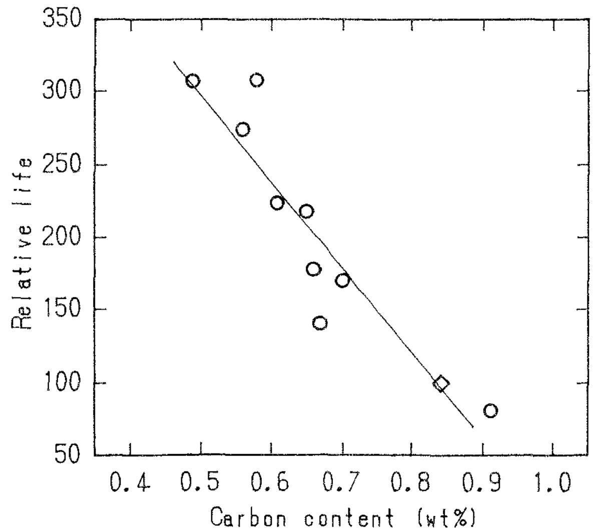

Fig.12 Relative life of the new grade shots evaluated by Ervin test machine

in Table 7 compared with popular materials normalized in SAE J441. Contrary to cast steel shot, the carbon content was increased up to 0.8% to obtain a high hardness at about HV700. Since cut wire has originally higher toughness than cast steel shot, it is possible to increase the carbon content without worring about the penalty of brittleness.

TEST RESULTS- First, shot durability was studied by using a centrifugal type shot peening machine. The relation between the amount of broken shot and accumulative peening time was obtained as shown in Fig.13. New cast steel shot ranging from 0.84 to 1.0mm diameter were prepared and hardened-tempered to hardness HV700. Pre-conditioned cut wire was prepared in 0.8mm diameter particles with hardness HV700 Conventional cast steel shot was made with the composition shown in Table 6 and a hardness of HV700. Shot peening was carried out with a shot flow of 0.75kg/sec at the speed of 106m/sec. The arc height was 1.0mmA. Broken shot was removed with a screen size of 0.71mm.

It is clearly shown that the new shots exhibit longer life than conventional cast steel shot. The amount of the broken shot for new pre-conditioned cut wire, at an accumulated peening time of 10ksec for example, is less than a tenth of that of conventional cast steel shot and new cast steel shot is less than a half.

The peening effect of the new shot media was studied, as a next step. Figure 14 shows the fatigue properties of test gears hard peened with these shot media. The peening intensity was 1.0mmA. No big difference is observed among the new and conventional shots. Therefore, these new shot media are expected to be of practical use as a long life peening media maintaining the benefits of hard peening.

CONCLUSIONS

The study was carried out on the selection of suitable carburizing steel for hard shot peening, beads and dual shot peening technology, and long life hard shot media. The results are summarized as follows.

(1)High performance carburizing steel:DSG1, 0.2C-Si<0.05-P<0.015-1Cr-0.4Mo, was selected as a steel for hard shot peening. DSG1 showed higher fatigue strength than conventional steel SCM420 both in carburized and hard peened gears.

(2)By applying beads shot peening after hard peening, further improvement of fatigue resistance was achieved. In spite of its lower intensity, beads peening provides higher residual compressive stress at the surface and just below it.

(3)In order to expand hard shot peening technology, a new type of hard and tough shot media were developed. A middle carbon cast steel shot and high carbon pre-conditioned high strength shot were created. These new media have confirmed prolonged lives and provide sufficient peening intensity.

Table 6 Chemical composition of cast steel shots

(wt.%)

	C	Si	Mn	P	S
New grade	0.50	0.50	0.30	<0.015	<0.015
Conventional	0.85/ 1.20	<0.40	0.60/ 1.20	<0.050	<0.050

Table 7 Chemical composition of steel cut wires

(wt.%)

	C	Si	Mn	P	S
New grade	0.82	0.25	0.45	<0.030	<0.030
Conventional	0.45/ 0.75	0.10/ 0.30	0.60/ 1.20	<0.045	<0.050

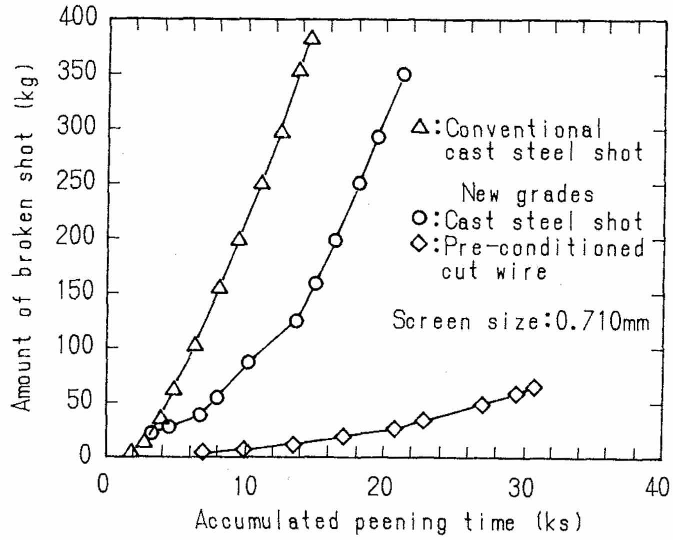

Fig.13 Comparison of steel shot life evaluated by the peening machine

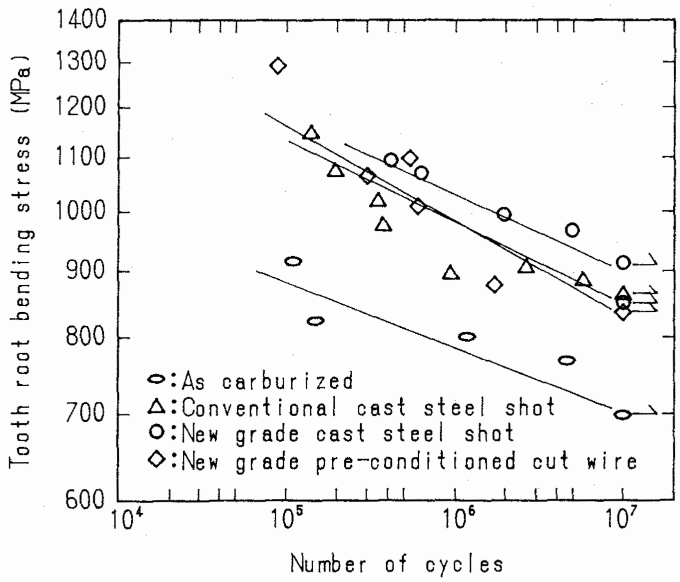

Fig.14 Comparison of fatigue properties for gears shot peened by conventional and newly developed media

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