

# Modeling of residual stress on blasted surface using indenting method

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## 1. Introduction

The blast process applied on work surfaces is most effective in improving fatigue strength for moving components such as; crankshafts, gears, turbine blades etc., and contributes to the size reduction of products[1, 2]. However, the compressive residual stress in work surface layers caused by the blast process occasionally may produce undesired results, because most of the process conditions are, in the state of art, dependent on the skill of the workers. In minimum-cost processing, the process conditions in the blast process have not always been designed to optimize surface quality. For instance, over-peening may cause a decrease in fatigue strength and an increase in processing time to produce a desired maximum residual stress and/or a desired residual stress distribution.

Therefore, it is important that the maximum stress and the distribution in the residual stress can be estimated in order to design the optimal process conditions. Shot consisting of micro grains as blasting tools, however, come to complicate the blast process because of unknown factors in the statistical approach. Many researchers have discussed the generating mechanism of residual stress in blast process[3-7]. Procedures estimating residual stress distribution in the blast process are shown in Table 1. The indenting method seems to be useful for analyzing the residual stress, because covering the work surface with uniform dimples can simplify the effect of shot on the residual stress in practical blast processes.

In the following, the generating mechanism of residual stress in a blast process is analyzed experimentally using the indenting unit with a single crystal diamond indenter, where various errors can be compensated by optimizing the soft supporting mechanism. These results are compared with those in FEM analysis in order to discuss the compatibility of both processes.

Table 1  
 Estimation of residual stress distribution in blast process

Estimation method	FEM[4,5]	Estimation [6]	Quasi estimation [7]	Indenting
Parameter compatibility	×	△	△	○
Normalization to optimize process conditions	×	×	△	○
Simulation on production process	×	×	△	○
Estimation time	○	○	△	×

## 2. Experimental procedure and conditions

### 2.1 Blasted surface modeling with indenting method

A work surface is treated by colliding a large number of shot in the blast process. Here, the surfaces on which various shot collide repeatedly and the resulting overlapped dimples are modeled as normalized surfaces indented with a large number of uniform dimples at a regular pitch. Fig. 1 shows the compatibility of the control factors to produce similar surface quality in both processes.

### 2.2 Experimental equipment for indenting

It is very difficult to indent a uniform depth precisely on a conventional machine tool, because there are many position errors of the indenter relative to a work surface. In order to indent on work surfaces at several microns deep, an indenting unit has been newly developed with the use of a single crystal diamond indenter supported by parallel leaf springs with optimal damping. The experimental apparatus is shown schematically in Fig. 2.

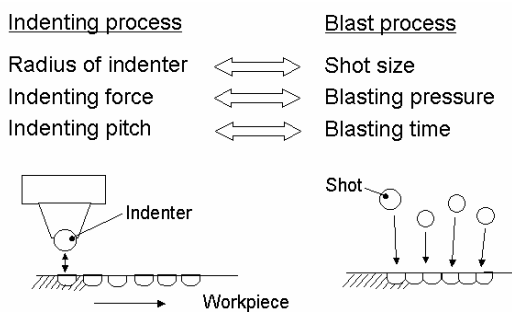


Fig.1. Compatibility of control factors in both processes

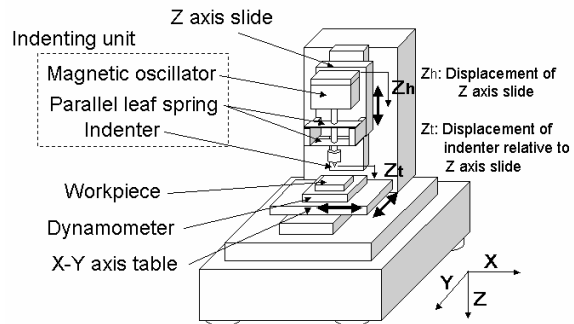


Fig.2. Experimental apparatus for indenting process

This indenting unit was installed on the quill of a tabletop NC milling machine. The indenting unit can compensate various sensitive errors caused between the indenter and a work surface, such as table motion error, thermal deformation of the workpiece relative to the indenter, chucking errors, and/or out-of-flatness of work surfaces. The displacement of the indenter ( $Z_t$ ) is relatively small, even if the displacement of the Z axis slide ( $Z_h$ ) is large (see Fig. 2). The contact of the indenter with the work surface was monitored by a piezo-type dynamometer(Kistler9257B). The indenting force ranged from 40mN to 3.3N in the experiments. The dimple depth of the indenting process is controlled by positioning the Z axis slide, according to the correlation among  $Z_h$ , indenting force and the dimple depth.

### 2.3 Experimental procedure

Indenting experiments were carried out using the above-mentioned indenting unit. The contact starting point can be detected with an accuracy of  $\pm 1\mu\text{m}$  displacement ( $Z_h$ ; see Fig. 2) in the Z axis slide by the dynamometer. Work surfaces were formed with a large number of uniform dimples at a regular pitch from 2 to 100 $\mu\text{m}$ . Experimental conditions are shown in Table 2. The blast process was carried out on an air blast machine (Fuji Work Co. Ltd., "Newblaster"). Workpieces (W20mm×B20mm×T10mm), 0.5%C annealed steel, were lapped to less than 0.1 $\mu\text{m}$  Ra after grinding in advance of the experiments.

The residual stress in work surface layers was measured using an X-ray method. The distribution of residual stress was obtained by repeated X-ray measurement on the work surface, each time removing 5 $\mu\text{m}$  deep using electrochemical polishing. The residual stress is defined as the average of the stresses in the X and Y directions for the homogeneous work surfaces treated.

Table 2 Experimental conditions

Indenting process	
Indenting speed	2 cycles/s
Dimple pitch	10, 20, 40, 50, 100 $\mu\text{m}$
Indenter	R 20 $\mu\text{m}$ . Single crystal diamond tip
Blast process	
Equipment	air type, air nozzle; $\phi$ 9 mm
Shot	size; $\phi$ 35-55 $\mu\text{m}$ material; glass (HV $\approx$ 900)
Blasting	time; 10 s pressure; 0.2 MPa distance; 100 mm
Workpiece	
Material	0.5%C steel (annealed)
Hardness	HV 240

## 3. Results and discussion

### 3.1 Indenting method

Fig.3 shows the relation between indenting force and dimple depth, when a spherical indenter of 20 $\mu\text{m}$  in radius was used. The dimple depth increases almost linearly with the increase of indenting force, although the correlation between them is in general considered linear to the square of the indenting force. Dimples of  $2.0\pm 0.2\mu\text{m}$  deep correspond to an indenting force of  $0.64\pm 0.064\text{ N}$ . Parallel leaf springs are inserted between an indenter and a tool holder. Fine control of the indenting force, with the compliance control mechanism, follows coarser positioning control of  $Z_h$ . The indenting force forming a dimple should be similar to one loaded by individual blasting shot for the purpose of evaluating the blast process. The normal force in individual blasting shot is calculated to be approximately 0.64N, according to a report[8]. Here, the indenting force similar to the blast process, is taken to be 0.64N.

### 3.2 Coverage and residual stress

The blasted surfaces are produced by a large number of blast shot colliding with the work surface. The characteristics on a processed work surface would depend on the probability of colliding with the same area on the surface. The number of dimples on a work surface increases with increasing processing time. Ideally, a standard state called "full coverage", or "coverage 100%" occurs when all the work surface is covered with dimple

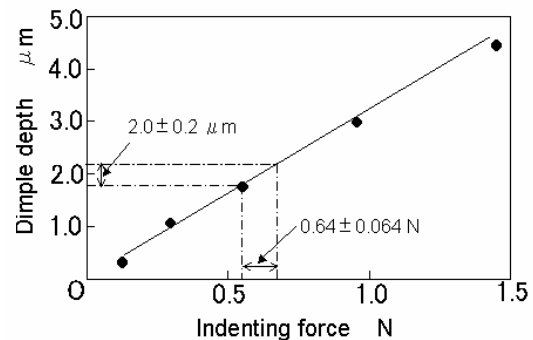


Fig. 3. Relation between indenting force and dimple depth

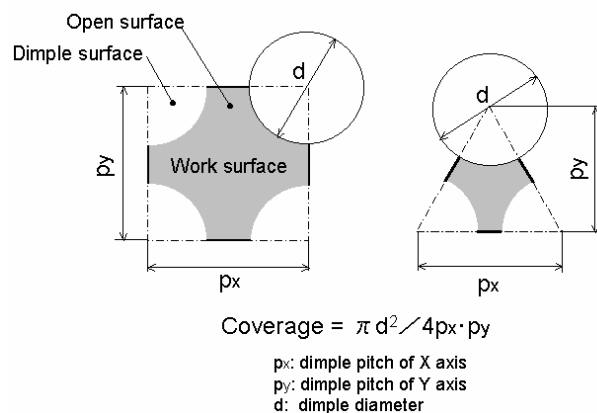


Fig.4. Geometry of indenting with uniform pitch coverage

patterns, with neither any remaining open area of pre-finished surface nor any area of overlapped dimple patterns. In actual practise, the dimple pattern is circular in the indenting process. Fig. 4 shows geometry of indenting with uniform pitch coverage.  $p_x$  and  $p_y$  are described as  $p$  when  $p_x = p_y$ . The indenting experiments were done at coverages from 2% to 300% on various dimple pitches.

The influence of the coverage on the maximum residual stress is shown in Fig. 5. The experiments were carried out at an indenting speed of 2 cycles/s.

It is apparent that the compressive residual stress in work surface layers increases significantly with increasing the coverage, up to about 200%. The compressive residual stress ranges from -100MPa at a coverage of 2% to -470MPa at 100%. The plastic regions below a dimple increase in size with increasing the coverage. Thus, it was recognized that residual stress strongly correlated with the coverage.

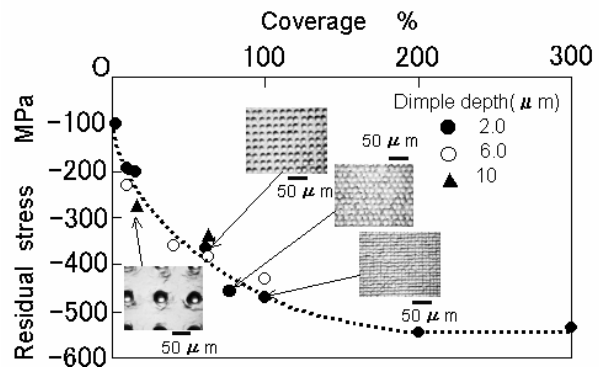


Fig. 5. Influence of coverage on maximum residual stress

3.3 Plastic regions  
A half width in the X-ray diffraction shows a degree of the strain of polycrystals in a work surface layer. The influence of the coverage on a half width in the indenting process is shown Fig.6. It is clear that the half width in the blast process is similar to that in the indenting process at a coverage over 100%.

This means the strain of polycrystals in a work surface layer is comparable in both processes. Fig.7 shows Vickers hardness measured every 5 μm deep from the work surface. Each plot is the mean value of five Vickers hardness measurements. The hardened regions in the work surface layer increase with the increase of dimple depth in indenting, in accordance with the increasing plastic regions in a work surface layer. The hardened regions in both processes are approximately 60 μm. As a result, it seems that the effect of the collision speed on the depth of plastic regions would be negligibly small, because the processed depth might be shallow in indenting and blast processes.

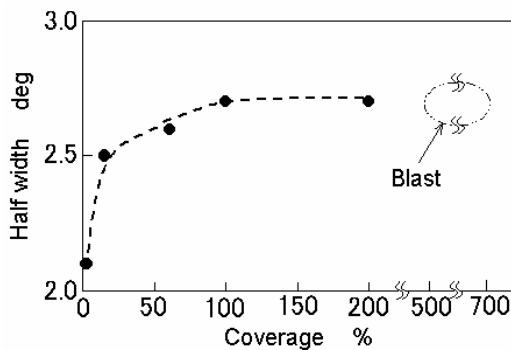


Fig.6. Influence of coverage on half width in indenting process

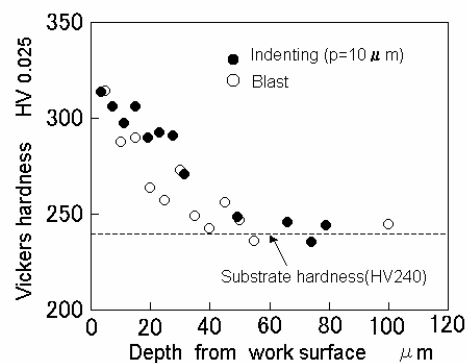


Fig. 7. Vickers hardness distributions of work surfaces treated using indenting and blast processes

### 3.4 Elastic-plastic analysis of plastic regions in indenting method

The finite element method is applied to analyze plastic regions generated in the indenting process. A rigid spherical indenter of 20μm in radius is shown as a two-dimensional plane strain model. The finite element mesh of the layered half-space. MARC v6.2 was used to solve the FEM. The material properties of the workpiece were as follows: Young's modulus; 206GPa, Poissons ratio; 0.3, yield stress; 300MPa, workpiece hardening slope; 2.06GPa, frictional coefficient; 0.2. Fig. 8 shows examples of plastic regions analyzed in the indenting process. It

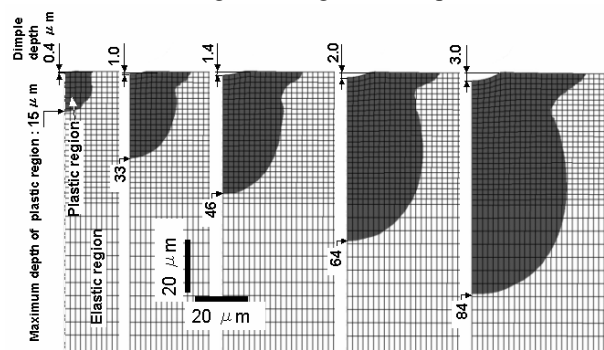


Fig. 8. Influence of dimple depth on plastic regions (FEM analysis)

is apparent that plastic regions increase with increasing indenting depth. The maximum depth of plastic regions at the center between two adjacent dimples with dimple depth  $2.0\ \mu\text{m}$  is  $64\ \mu\text{m}$ . This result in the FEM analysis is similar to the maximum depth of hardened regions,  $60\ \mu\text{m}$  deep, which seems to be in the plastic region. It indicates that it is possible to use FEM analysis to estimate the maximum depth of plastic regions.

### 3.5 Distributions of residual stress

Fig. 9 shows the distribution of residual stress below work surfaces created by blast and indenting processes. In the figure, the coverage is over 100% in the indenting process, and over 500% in the blast process. Almost the same stress distributions are obtained in the work surface layer to  $50\ \mu\text{m}$  deep in both processes. The maximum compressive residual stress, about  $-450\ \text{MPa}$ , exists in the vicinity of the work surface in each process. It was found that the distribution of residual stress in the indenting process simulated that in the blast process. As a result, it seems to be that the coverage in the blast process is excessive, even though the blasting conditions in normal production process were applied in the blasting experiments. It can be said that the coverage would be sufficient at around 200% in the blast process.

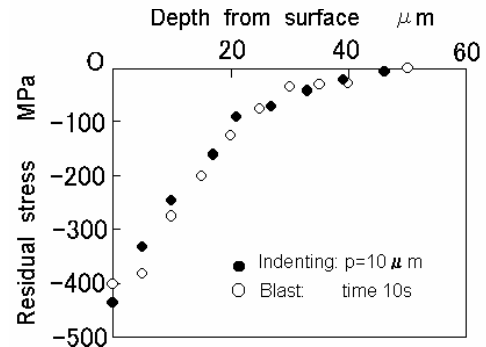


Fig.9. Residual stress distributions (coverage > 100%)

### 3.6 Work surface profiles

In the indenting process, the spherical shape of an  $R\ 20\ \mu\text{m}$  indenter is printed on a work surface regularly. On the other hand though, various shot collide and overlap on previous dimples, so that a work surface is irregular in the blast process. Undulations with  $50\text{--}60\ \mu\text{m}$  in period are observed in both work surface profiles, in accordance with crystal sizes of work material. The P-V value of the work surface profile is about  $2\ \mu\text{m}$  in each process. Therefore work surfaces in both processes would have similar characteristics.

## 4. Conclusions

The relationship between the indenting process and the blasting process has been discussed for residual stress and work surface profile. As a result, it is made clear that the surface characteristics treated in the blast process can be realized in the indenting process. The following conclusions were summarized:

- (1) Plastic regions in the indenting process were estimated by a distribution of Vickers hardness and a half width in the X-ray diffraction pattern as well as the blast process. As a result, it is shown that the depth of a plastic region in the indenting process can simulate one in the blast process, and that the strain in polycrystals on a work surface layer can be comparable in both processes.
- (2) The residual stress distribution in the indenting process can simulate one in the blast process.
- (3) The compressive residual stress in the indenting process increases with the increase of the coverage up to almost 200%. This means the possibility of reducing blasting time drastically in present production lines.

## References

- [1]W.Welsch. Lubricating properties of shot peened gears. 52nd Annual Meeting in Kansas City, STLE, 1997, 1.
- [2]P.G.Bailey, J.M.Whalen. Shot peen controls and aircraft engine requirements. International Conference on Surface Engineering, Toronto., 1990, 379.
- [3]Tosha K, Iida K. Surface residual stresses produced by shot peening and grit blasting. J. JSAT., 1998, 42(2), 63. [in Japanese].
- [4]Mori K, Osakada K, Shiomi M, Okada T. Three-dimensional finite element simulation of plastic deformation and residual stress in shot-peening (Deformation by single shot). J. JSME Trans. 1993, 59(566), 2420. [in Japanese].
- [5]Mori K, Osakada K, Matsuoka N. Rigid-plastic finite element simulation of peening process with plastically deforming shot. J. JSME Trans. 1995,61(586),1337. [in Japanese].
- [6]Y.F.Al-Obaid. A rudimentary analysis of improving fatigue life of metals by shot peening. J. Appl. Mech. ASME Trans., 1990, 57, 307.
- [7]Watanabe Y, Hasegawa N, Matsumura Y. Simulation of residual stress distribution on shot peening. J. Soc. Mat. Sci.,Japan. 1995, 44(496), 110. [in Japanese].
- [8]K. Ogawa, T. Asano. Theoretical prediction of residual stress produced by shot peening and experimental verification for carburized steel. Materials Science Research International, 2000, 6(1), 55.