RESEMBLANCE BETWEEN RESIDUAL STRESS PRODUCED BY SHOT PEENING AND THERMAL STRESS BY TEMPERATURE DISTRIBUTION

K. Kanazawa[1] and T. Kamiyama[2]

[1] Department of Precision Mechanics, Chuo University,
Bunkyo-ku, Tokyo, 112-0003 Japan
[2] Mitsubishi Heavy Industries,
Nakamura-ku, Nagoya-shi, 453-8515 Japan

ABSTRACT

A resemblance between residual stress produced by shot peening and thermal stress by temperature distribution was pointed out to understand how residual stress generates at the surface layer of works by shot peening. The model of generation of compressive residual stress at the surface layer was proposed as that the residual stress is produced by constraining lateral strain by Poisson's ratio corresponding with compressive strain at the surface layer. Stress distribution produced by constraining lateral strain can be estimated by the same method as calculation of thermal stress due to a temperature distribution at the surface layer. Thermal stress for various temperature distributions at the surface layer are fairly similar to distributions of residual compressive stress obtained by shot peening treatments under various conditions. Lateral strain distribution corresponding with the optimum residual stress distribution for fatigue strength will be obtained from the thermal strain model proposed. This information must be very useful for selections of shot peening conditions.

INTRODUCTION

Shot peening is one of the most important treatment for mechanical parts such as springs, gears and so on, whereby the material’s surface is bombarded with round or spherical shots, producing a thin layer of high-magnitude residual compressive stress. Residual compressive stress at the surface of the mechanical parts is effective to increase fatigue strength and/or fatigue life under cyclic loading.

Distribution of residual compressive stress depends on conditions of shot peening treatment such as the composition, hardness and size of the peening shots, the transferred energy at impact, the percentage of coverage, material and geometry of works, and so on. It is necessary how to select conditions of shot peening treatment to obtain a suitable distribution of residual stress for high performance against fatigue fracture. But, relationship between the conditions of shot peening process and the residual stress is understood empirically only.

Distribution of residual stress by shot peening treatment may be obtained analytically using finite element method. A dynamic rigid-plastic finite element method for simulating high speed plastic deformation in the shot peening processes was proposed by Mori et al.[1] on the basis of the finite deformation theory of plasticity. Three dimensional plastic deformation and residual stress distribution in rectangular blocks peened with single rigid spherical shot were computed. But, residual stress produced by shot peening with multiple shots has not been analyzed.

On the other hand, when a distribution of residual stress is measured for a work peened under some conditions, is it possible to estimate what happens at the surface layer of the work? If it's possible, what should happen at the surface layer of the work can be estimated for an ideal distribution of residual stress. This information is very useful for selections of shot peening conditions.

In this paper, a resemblance between residual stress produced by shot peening and thermal stress by temperature distribution is remarked to understand how residual stress generates at the surface layer of Works by shot peening under various conditions.

MODELING AND CALCULATION METHOD

The mechanism of generation of compressive residual stress at the surface layer of a work by shot peening is considered as follow. That is, the residual stress is produced by constraining lateral strain by Poisson's ratio corresponding with compressive strain at the surface layer. The generation of residual stress by this plastic deformation model is the same as that of thermal stress produced by constraining thermal strain due to temperature distribution at the surface layer of a bulky material.

The distribution of the lateral strain has not been analyzed for peened works such as Almen strips, and then, there is no method to estimate distribution of residual stress by shot peening. But, if the distribution of the lateral strain could be estimate, distribution of residual stress can be calculated by converting the lateral strain to thermal strain due to temperature distribution. The conversion of plastic deformation model to thermal strain model is shown in Figure 1 schematically.

When the relationship between distributions of lateral strain and of the residual stress, that is, the relationship between distributions of temperature and of thermal stress is clarified, lateral strain distribution corresponding with the optimum residual stress distribution for fatigue strength will be obtained.

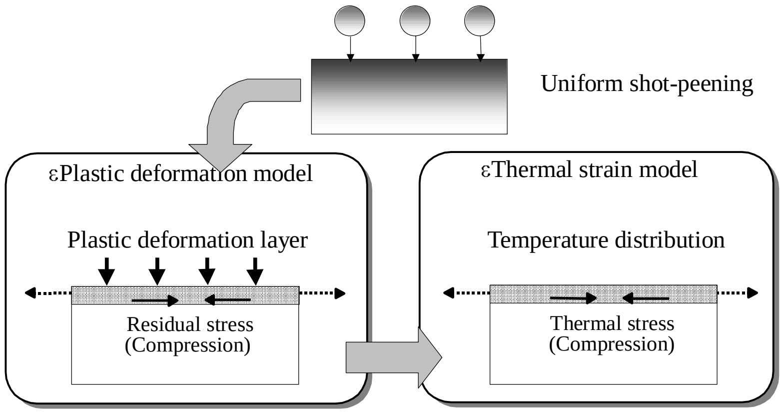

Figure 1: Conversion of plastic deformation model to thermal strain model

According to the elemental theory of elasticity [2], for a beam with the *xz*-plane as its neutral plane, the *x*-direction as its longitudinal direction and a thickness 2*c*, under assumptions of normal stresses σ_z and σ_y along *z*- and *y*-directions, respectively being zero, thermal stress σ_x is obtained as follow:

$$\sigma_x = -\alpha E T(y) + \frac{1}{2c}\int_{-c}^{c} \alpha E T(y) dy + \frac{3y}{2c^3}\int_{-c}^{c} \alpha E T(y) y dy \tag{1}$$

where *T* is temperature which is a function of *y* and is independent of *x* and *z*, and *E* and α are Young's modulus and coefficient of thermal expansion, respectively. An example of the beam with one dimensional temperature distribution is shown in Figure 2.

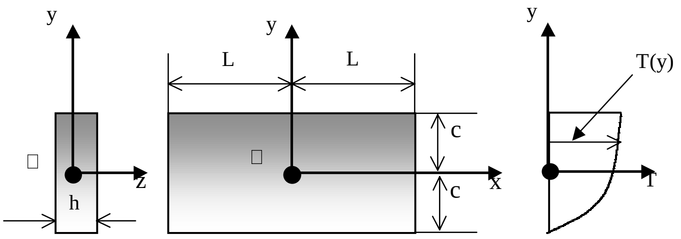

Figure 2: Beam with one dimensional temperature distribution

If we express the temperature distributions by following equations

$$\begin{cases} T(t) = 0 \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (-1 \le t \le k) \\ T(t) = T_0\left\{1 - \dfrac{(1-t)^n}{(1-k)^n}\right\} \cdots\cdots\cdots (k < t \le 1) \end{cases} \tag{2}$$

where t is y/c and T_0 is temperature at the surface of t = 1, various temperature distributions are obtained depending on parameters of k and n as shown in Figure 3. Thermal stresses due to temperature distributions of Eqn.2 are obtained from Eqn.1 as follow:

$$\begin{cases} \dfrac{\sigma_x}{\alpha E T_0} = \dfrac{(1-k)}{2}\left(\dfrac{n}{n+1}\right) + \dfrac{3t(1-k)}{2}\left\{\dfrac{1+k}{2} - \dfrac{k}{n+1} - \dfrac{1-k}{(n+1)(n+2)}\right\} \cdots\cdots (-1 \le t \le k) \\ \dfrac{\sigma_x}{\alpha E T_0} = -\left\{1 - \dfrac{(1-t)^n}{(1-k)^n}\right\} + \dfrac{(1-k)}{2}\left(\dfrac{n}{n+1}\right) + \dfrac{3t(1-k)}{2}\left\{\dfrac{1+k}{2} - \dfrac{k}{n+1} - \dfrac{1-k}{(n+1)(n+2)}\right\} \cdots\cdots (k < t \le 1) \end{cases} \tag{3}$$

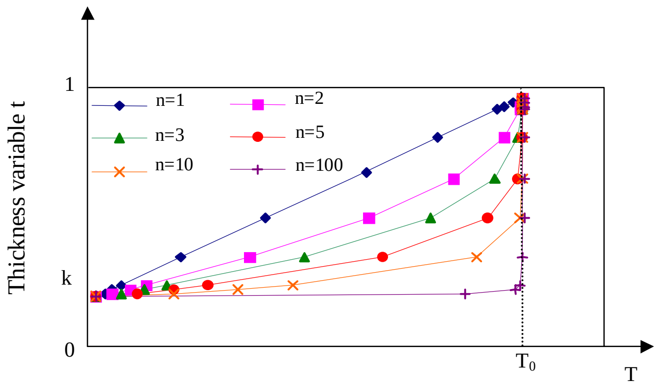

Figure 3: Temperature distributions expressed by Eqn 2

Rectangular Almen strips are used to evaluate intensity of treatments of shot peening. The Almen strip is peened against its one side plane and arc height of the curved Almen strip is measured. In thermal stress model, arc height of a curved beam due to the temperature distribution expressed by Eqn. 2 can be obtained. The third term of Eqn.1 expresses stress component related to virtual bending moment M divided by modulus of section. In this case, radius of curvature R is

$$\begin{aligned} R &= EI/M \\ &= \frac{2c}{3\alpha T_0(1-k)\left\{\dfrac{1}{2}(1+k) + \dfrac{1-k}{n+2} - \dfrac{1}{n+1}\right\}} \end{aligned} \tag{4}$$

where I is moment of inertia of area. Arc height A_h defined in Figure 4 is

$$\begin{aligned} A_h &= R(1-\cos f) \\ &= R\left(1-\cos\frac{L}{2R}\right) \end{aligned} \qquad (5)$$

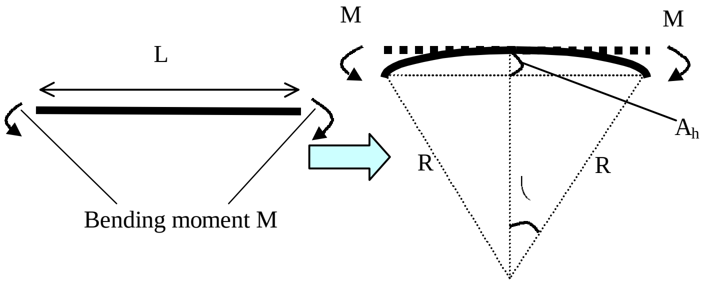

Figure 4: Definition of arc height

RESULTS OF CALCULATION

Thermal stress distributions obtained by Eqn.3 are shown in Figure 5 under a condition of $k = 0.5$ taking n as a parameter. Peak position of compressive thermal stress and crossing point which is the position for thermal stress to change from compression to tension, move to inside from the surface with increasing value of n. The pattern of thermal stress distribution changes from C Type where the position of the maximum compressive stress is located at the surface to S Type where the position is located at the inside. These distributions of thermal stress are similar to distributions of residual stress observed on peened strips [3].

Figure 6 shows non-dimensional arc height $A_h/2c$ for conditions of $L/2c = 95$ and $aT_0 = 0.0025$ as a function of k or n. Arc height increases with decreasing value of k up to 0 and with increasing value of n, that is, when temperature distribution becomes uniformly at the surface layer.

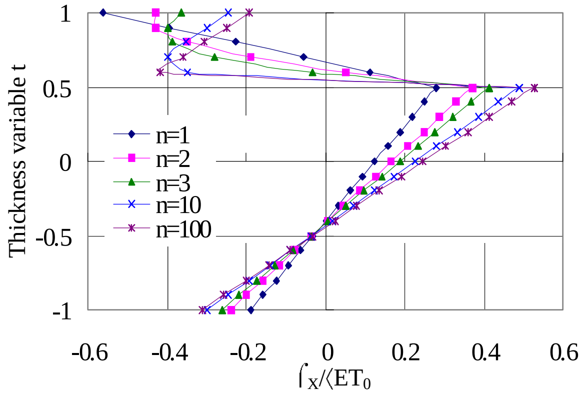

Figure 5: Normalized thermal stress distribution along thickness variable *t*

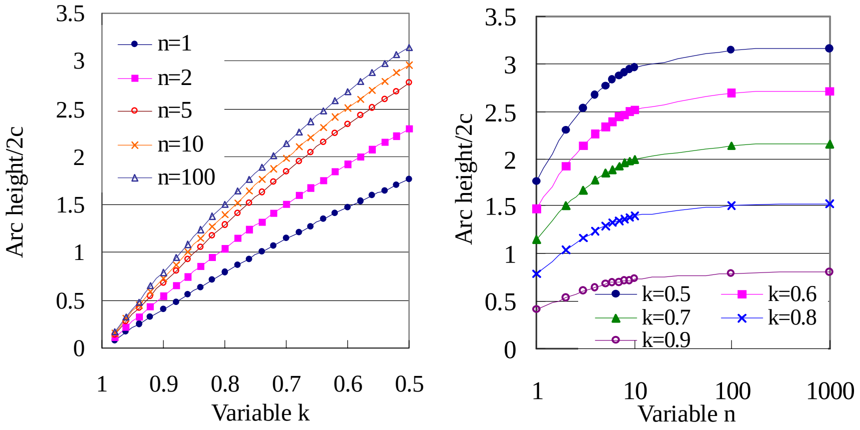

Figure 6: Dependence of non-dimensional arc height on variable *n* and *k*

COMPARISON WITH EXPERIMENTAL RESULTS REPORTED

Change in Distribution of Residual Stress and Arc Height with Degree of Shot Peening Processes

Ohno et al. [3] reported changes in distribution of residual stress with increasing number of passes for works on conveyor belts moving through a shot peening equipment. The examples of the results are shown in Figure 7(a) and 7(c). In the experiments cut wire shots with size of 1mm in diameter were used for rectangular works with sizes of 19mm in width, 76mm in length and 3mm in thickness. Shot speeds were 33m/s and 49m/s for results of Figure 7(a) and 7(c), respectively.

In thermal strain model, increment of number of passes can be regarded as increment in area of temperature distribution. Let us express the area of temperature distribution for the first pass by S_1 and for mth pass by S_m. The change in the area of temperature distribution with increasing number of passes m is expressed temporary by Eqn. 6 according to increment in coverage under shot peening treatment [4].

$$S_m=1-(1-S_1)^{m} \tag{6}$$

Figure 8 shows the processes of area increment of temperature distribution. That is, at the early stage the distribution is linear as $T_o'k'$ which is parallel to T_ok. After for the distribution coinciding with the line T_ok, it follows by Eqn.2.

Examples of calculation results of thermal stress with change in temperature distribution are shown in Figure 7(b) and 7(d) under following two assumptions. The first is the temperature distribution at the final stage expressed by Eqn.2 where exponent n is 2 and 5 for Figure 7(b) and 7(d), respectively. The second is that the percentages of the area increment of temperature distribution at the first pass to the area of temperature distribution of the final temperature distribution is 14% and 21% for Figure 7(b) and 7(d), respectively. Compressive thermal stress at the surface increases with increasing number of passes at the early stage. After the stage, it becomes small depending on the setting conditions, and the peak position of the compressive thermal stress moves from the surface to the inside. These tendencies coincide qualitatively with experimental results very well.

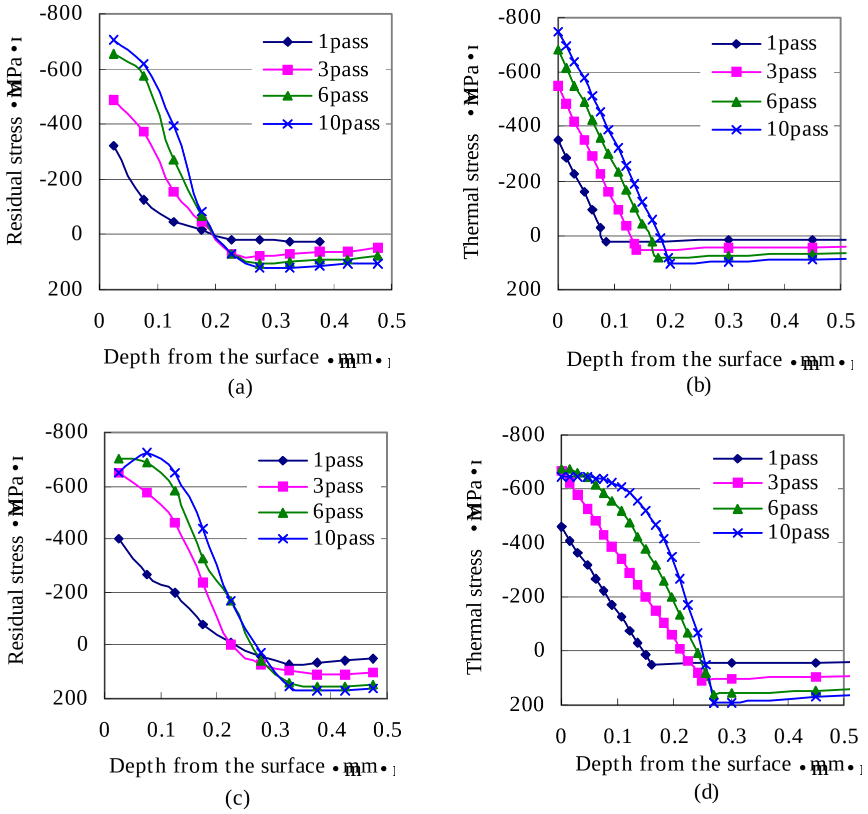

Figure 7: Distributions of residual stress by shot peening and distribution of thermal stress obtained by proposed method

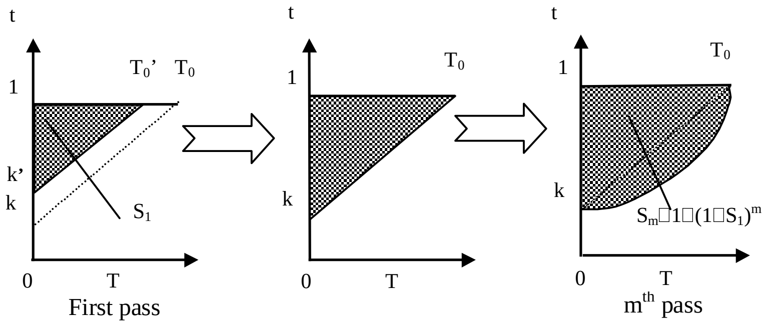

Figure 8: Method of area increment of temperature distribution

Examples of calculation results of arc height with change in temperature distribution are shown in Figure 9 under the conditions corresponding with Figure 7(b) and 7(d). The value of arc height increases and becomes to a saturated value. This tendency coincides qualitatively with experimental results fairly well too.

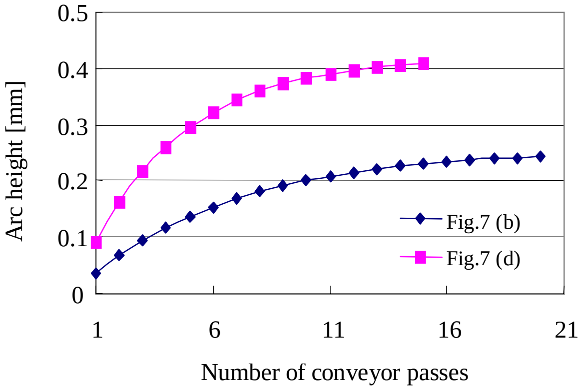

Figure9: Change in arc height with increasing number of conveyor passes

Double Shot Peening

Treatments of double shot peening are effective to improve compressive residual stress at the surface layer of works. Generally, the first treatment is carried out using large shots to get thick layer with residual compressive stress and the second is carried out using small shots for the peak position of residual compressive stress to be located at the surface of the work.

In thermal stress model, residual stress produced by double shot peening can be understood as the results of superposing two types of temperature distributions, which concept is shown in Figure 10. One is that a high level temperature distributes from the surface to the deep position and the other is that temperature change drastically at the thin layer of surface.

Figure 11 shows an example of the thermal stress model for double shot peening. The position of peak compressive residual stress is located at the surface which tendency describes the experimental result reported [5].

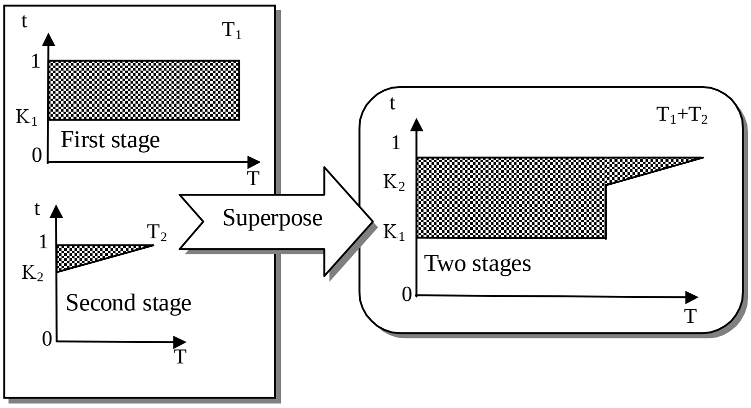

Figure 10: Concept of double shot peening in thermal strain model

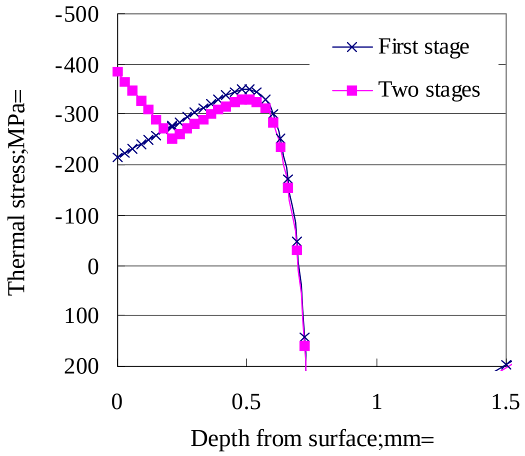

Figure 11: Thermal stress distribution by superposing two types of temperature distributions

CONCLUSION

A resemblance between residual stress produced by shot peening and thermal stress by temperature distribution was pointed out to understand how residual stress generates at the surface layer of works by shot peening.

The model of generation of compressive residual stress at the surface layer was proposed as that the residual stress is produced by constraining lateral strain by Poisson's ratio corresponding with compressive strain at the surface layer.

Stress distribution produced by constraining lateral strain can be estimated by the same method as calculation of thermal stress due to a temperature distribution at the surface layer. Thermal stresses for various temperature distributions at the surface layer are fairly similar to distributions of residual compressive stress obtained by shot peening treatments under various conditions.

Lateral strain distribution corresponding with the optimum residual stress distribution for fatigue strength will be obtained from the thermal strain model proposed. This information must be very useful for selections of shot peening conditions.

REFERENCES

1. Mori, K., Osakado, K., Shiomi, M. and Okada, T. (1993) Trans. Japan Soc. Mech. Eng. (A) **59**, 208.
2. Timoshenko, S. P. and Gooder, J. N. (1970) Theory of Elasticity, McGraw-Hill.
3. Ohno, A. and Miyazaki, N.(1957) J. Japan Soc. Testing Mat. **6**, 23.
4. Japan Society of Shot Peening Technology (1997) Methods and Effects of Shot Peening, The Nikkan-Kogyo Shinbun.
5. Toshino, H., Shigeno, K. and Takagi, N. (1987) Trans. Japan Soc. Spring Res. **32**, 31.