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EFFECT OF RESIDUAL STRESS BY SHOT PEENING ON FATIGUE STRENGTH OF LCV LEAF SPRING

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ABSTRACT–Spring is one of major suspension part of the light commercial vehicle (LCV). In the manufacturing process it is shot-peened to improve its fatigue strength. In this paper, residual stresses by shot peening were calculated through finite element analysis, and the effects of these residual stresses on fatigue strength of leaf spring were evaluated. Fatigue tests were performed with two kinds of specimens; one is actual leaf spring assembly, and the other is simulated 3-point bending specimen. Fatigue tests were performed under the loading condition that was measured on the proving ground. From the results, the maximum load-fatigue life relation of leaf spring was defined, and test results of 3 point bending specimen are in good agreement with those of leaf spring assembly. The effects of residual stresses by shot peening on fatigue strength of leaf spring is not large in the high load range, however, in the low load range, its effects were not negligible.

KEY WORDS : Suspension system, Leaf spring, Residual stress, Shot peening, Durability, Road load response, 3-point bending test, Fatigue strength, Fatigue design criterion

1. INTRODUCTION

To secure reliability satisfying required performance during design life of the vehicle, durability of the vehicle components should be guaranteed, firstly. Therefore, vehicle's durability gives priority to analysis and assessment of its endurance under the various environments and loading conditions and traveling capacity normally maintaining its required function. And this durability assessment of the vehicle is to assess not only its durability but also reliability. In such sense, durability assessment for the suspension system of the vehicle is very important. The purpose of the vehicle's suspension system is to protect the passengers and body from the shocks caused by vehicle moving over the irregular roads.

The typical suspension of the vehicle is an extremely complicated system consisting of two springs, four stops, two shock absorbers and one anti-roll bar.

Among them, spring is one of the major suspension parts of the vehicle. And, spring and dampers on the vehicle are mainly responsible for ride comfort and allow the body to roll and pitch (Feng, 2003; Kim, 1996).

Thus, since this suspension system of the vehicle is directly influenced to ride and handling, suspension part should have enough endurance during its lifetime to protect the passengers.

In this paper, a fatigue design criterion for leaf spring of LCV based on proving ground response was proposed. At first, residual stress distribution by shot peening performed to improve fatigue strength in the manufacturing process of leaf spring was analyzed using finite element analysis. And next, by using the maximum load of leaf spring assembly on the road load response, the fatigue load-life relation of LCV leaf spring was obtained from leaf spring assembly fatigue test. And also, in order to evaluate the effects of residual stress by shot peening to fatigue characteristics of leaf spring material and to develop an economical fatigue design method using simply simulated specimen, 3 point bending specimen tests were also carried out.

2. RESIDUAL STRESS ANALYSIS OF LEAF SPRING

Shot peening is one of the useful techniques for improv-

**Corresponding author.* e-mail: bae@yurim.skku.ac.kr ing fatigue strength of the mechanical components. By shot peening, compressive residual stresses are generated in the inner side of the material due to plastic strain by impact of the rigid shot balls. When external fatigue load acts on shot peened material of the mechanical components, since the compressive residual stresses generated in the process of shot peening mostly make alleviation the tensile stresses generating under actual driving condition, their fatigue strength or fatigue life can be effectively improved. Therefore, when shot peening condition was changed, it is important to predict the variation of compressive residual stresses in material of the component. So far, many investigators, for example, Kim (Kim, 2001), Schiffner (Schiffner, 1999) and Eleiche (Eleiche, 2001) have studied on these problems. By the way, since residual stress analysis of shot peened material are generally investigated on the single shot peening, their results could not consider stress variation due to multiple impacts in the process of shot peening, or sometimes, are overestimated. In order to improve these problems, the authors proposed a numerical analysis model for multiple impacts and its results. By using their analysis results we were assessed the effects of residual stress on fatigue strength of shot peened leaf spring for the light commercial vehicle (LCV).

2.1. FE Modeling

In this paper, to control the positions of the shot balls for multiple impacts, a plane-symmetric finite element analysis model was used. Two kinds of numerical analysis model, which are single impact (Figure 1) and multiple impacts (Figure 2), were constructed. In particular, in case of multiple impacts of Figure 2, impacting sequence was decided by changing the initial height of the shot balls impacting to the surface of material. Radius r is the distance from the center of peening material to the center of the shot ball in the impacted position. The positions of 5th and 6th are placed on 45° direction against 4-1-2 line. According to Aleksandrov and Pozharskii (1994), friction in the contact region is ignored. therefore friction coefficient between the surface of shot peening material and the shot ball assumes to be zero. The diameter and the velocity of the shot ball are 1.0 mm, 45 m/sec respectively.

The velocity of the shot ball was decided from the value showing that the maximum residual stresses were not nearly changed by the single impact.

Since the shot ball does not nearly strain in comparison with peening material, it was considered as a rigid body in FE modeling. And contacting boundary between the shot ball and peening material was constrained so as to not invade in each other.

Peening material for FEA modeling is SUP9, which is a material of leaf spring for the light commercial vehicle.

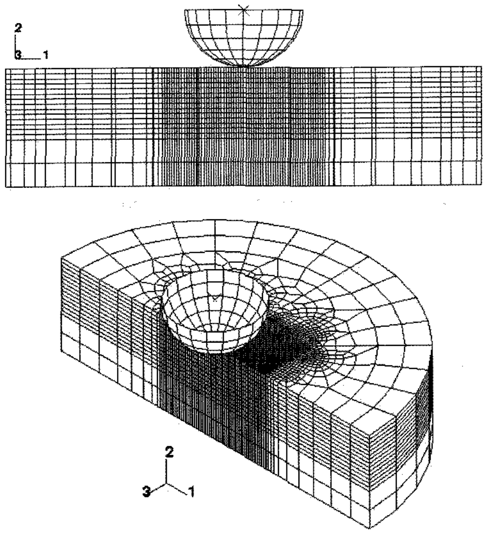


Figure 1. Plane symmetric finite element model for single impact.

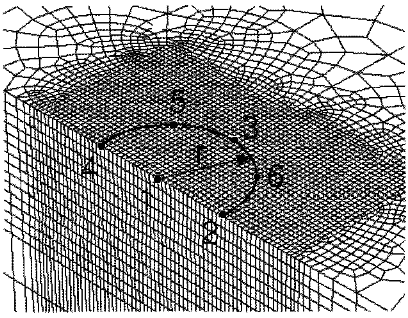


Figure 2. Positions of the shot balls in multiple impacts.

Table 1. Chemical composition of SUP9.

C	Si	Mn	P	S	Cr
0.62	0.26	0.92	0.014	0.01	0.98

Elastic modulus of SUP9, E=232 Gpa, Poisson's ratio, υ = 0.3. Chemical composition and the other mechanical properties of material are illustrated in Tables 1 and 2.

Although the analysis should consider the dynamic material properties due to the high velocity process, the present analysis considers the static material properties.

I-DEAS and ABAQUS Explicit 5.8, which are commercial package programs, were used in FEA modeling and elasto-plastic and dynamic analyses respectively.

An 8-node solid element was used in the analysis and the number of elements and nodes are 47538 and 51252 respectively.

2.2. The Results of FEA

2.2.1. Variation of residual stress by multiple impacts

Table 2. Hardening flow curve of SUP9.

Yield Stress MPa (Kgf/mm^2)	Strain Hardening Exponent. n	Strength Coefficient. K MPa (Kgf/mm^2)	True Fracture Stress, MPa (Kgf/mm^2)
1176 (120)	0.06	1764 (180)	1703 (173.8)

Figure 3 shows variation of residual stresses according to impacts of the shot balls for the shot ball diameter, d = 1.0 mm, shot distance, r = 0.150 mm, and shot velocity, v = 45 m/sec. In case of the 1st impact to be equivalent to single impact, magnitude of the maximum compressive residual stress at impacted indentation was calculated in 1,340 MPa, but, after the last impact, its magnitude was calculated in 1,057 MPa that is about 70% of the 1st impact.

Therefore, these results indicate that, after the 2nd impact, the compressive residual stresses considerably decreased by repeated impact, and the surface residual stresses in Figure 3 were also influenced.

2.2.2. Influence of the shot ball distance in multiple impacts

In difference with single impact, it is important to consider the shot ball distance in the analysis of multiple impacts.

Figure 4 shows the analysis results considered the shot ball distance (r) in case of shot velocity, v = 45 m/sec and shot ball diameter, d = 1.0 mm. As shown in Figures 4 and 5, when the shot ball distance is very near, the maximum compressive residual stress increased like as multiple step shot peening was conducted at the same position. When the shot ball was impacted at the edge of indentation as shown in Figure 5, compressive residual stress on the surface presented the maximum due to the effect of strain difference between the outer side and the inner side where was strained plastically.

When the shot ball distance is very long, since the interference effects between the impacted shot balls decrease, it shows that residual stress distribution is similar to single impact. Comparing the analysis results used the multiple impacts model and the single impact model, analysis results by multiple impacts model were mostly lower than those of single impact model.

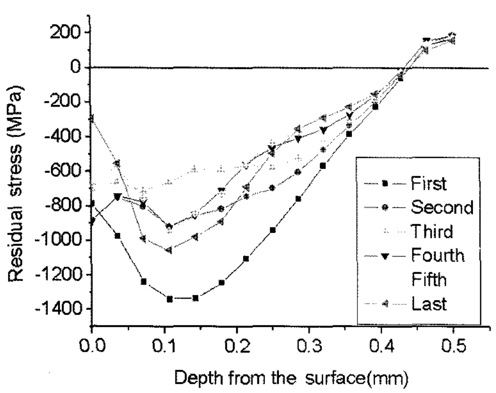


Figure 3. Residual stress profiles due to each impact.

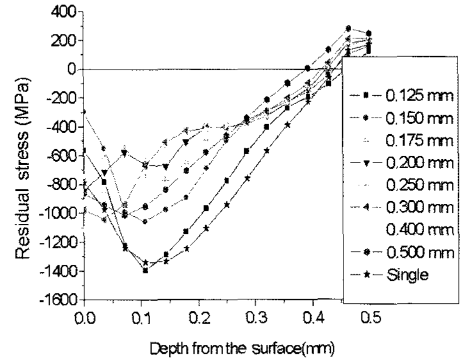


Figure 4. Residual stress profiles by multiple impacts with different distance r.

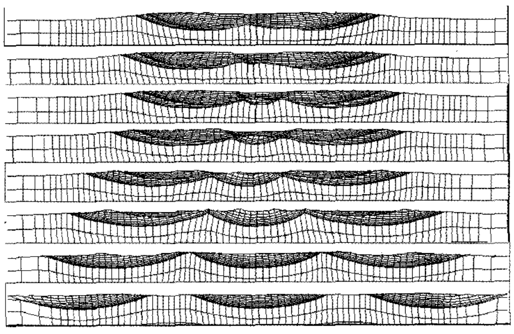


Figure 5. Deformed surfaces of work-piece with various shot distances at the symmetric plane.

Figure 6 shows the results of FEA and the experiments. The experimental results were obtained using the specimen arbitrarily selected from the actual manufacturing process of leaf spring. And also, the FEA results were calculated under the same condition with the actual manufacturing process (shot ball diameter, d = 0.8 mm, shot velocity, v = 61 m/sec). In case of single impact, the maximum compressive residual stress was estimated in 228% of the experimental value, and in case of multiple impacts, 136% of it. Therefore, it could find that analysis by multiple impacts is more reasonable than single impact. However, both the results by single impact and multiple impacts are larger than the experiments. Showing such results is due to the fact that, since the shooting angle of the shot ball was not 90 degree against the surface of leaf spring in the actual manufacturing process, the velocity component actually affecting residual stress generation was lower than 61 m/sec.

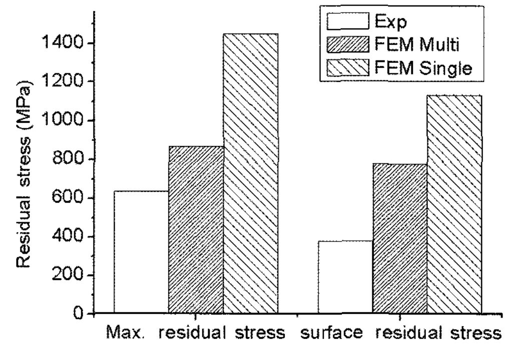
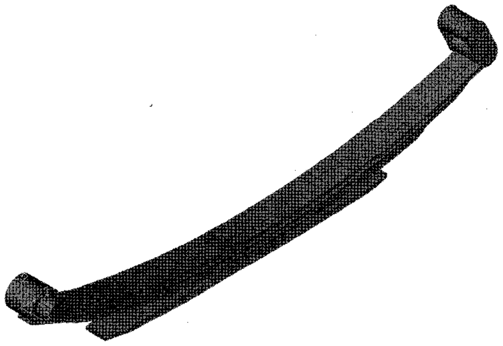
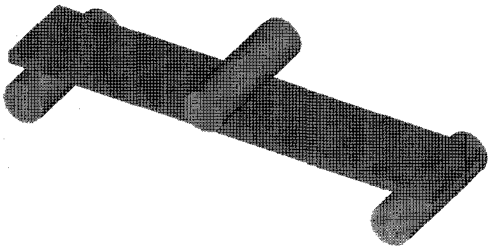


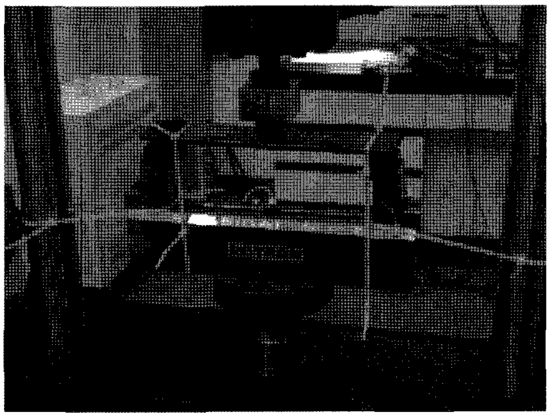
Figure 6. Comparison between the results of FEA and experiment.



(a) Leaf spring assembly.



(b) Simulated smooth specimen.



(c) 3 point bending fatigue test

Figure 7. Configuration of fatigue test specimen.

3. FATIGUE STRENGTH ASSESSMENT OF LEAF SPRING

In order to determine fatigue design criterion for the components of actual vehicles, it is necessary to provide fatigue data of the design components. The method for fatigue data acquisition is general to conduct fatigue tests under the condition arbitrarily made. However, since the fatigue design criterion determined under arbitrary condition does not cover actual conditions, it is difficult to attain economical and reasonable design as well as make reduction reliability on design.

Therefore, for reasonable design to satisfy design life of leaf spring assembly, it is necessary to determine the fatigue design criterion from the fatigue data obtained under the most severe actual condition. Thus, in order to develop the new fatigue design criterion for LCV leaf spring, it is necessary to determine fatigue load-life relation. In this paper, fatigue load-life relation was obtained by fatigue test under defined test specification. And the data measured on road load response was used to obtain the fatigue load-life relation to develop the new fatigue design criterion of leaf spring.

And also, in order to evaluate the fatigue characteristics of leaf spring material and to develop an economical fatigue design method using simply simulated specimen, 3 point bending specimen tests were also conducted [Bae, 2003]. And also, in this paper, through the 3-point bending fatigue test, the influence of compressive residual stress by shot peening was evaluated.

3.1. Specimen

Fatigue tests were conducted on two kinds of specimens; one is actual leaf spring assembly for LCV, and the other is the simple smooth specimen for 3-point bending test.

The 3-point bending fatigue test specimen of Figure 7 (a) was prepared from actual LCV leaf spring assembly. To investigate the influence of compressive residual stress by shot peening process, two kinds of test specimens were fabricated with and without shot peening from a lot under same manufacturing process. Length of specimen (L = 280 mm) of Figure 7(b) was made by 4 times of specimen width (w = 70 mm) to apply uniform load at the center of specimen by saint venant principle.

3.2. Test Equipment and Condition

Hydraulic servo multi-axial fatigue test equipment (Instron 880, capacity; 50 ton)) was used for fatigue test of leaf spring assembly. Since this case is the large scale deformation problem, frequency applied was 0.2–3.0 Hz under displacement control. Table 3 illustrates fatigue test condition of leaf spring assembly.

During the fatigue test, influence of shackle on the both end sides of leaf spring assembly was not considered. However, in stead of shackle, each leaf spring end was supported with roll bearing to simulate longitudinal deformation by bending of leaf spring.

And the guide jigs for slide bearing were fixed on the test bed. These guide jigs help longitudinal deformation of leaf spring assembly when load was applied.

Hydraulic servo fatigue test equipment (MTS 810, capacity; 10 ton) was used for 3-ponit bending fatigue test.

Special jig for 3-point bending fatigue test was fabricated. By machining the shape of jig in triangular type, vertical load could be uniformly applied to the specimen, and prevented slip by bending deformation during fatigue load applied to specimen.

Applied maximum fatigue load and displacement were determined from the test data of Figure 8 based on proving ground response. (max. load = 1246 kg_f, max. displacement = 110 mm)

In order to determine the fatigue limit of leaf spring, fatigue test was conducted using the 10% load reducing method from the maximum fatigue load until the fatigue limit was obtained under test condition. Fatigue life of specimen was determined as the number of cycles to failure. Table 3 illustrates 3-point bending fatigue test condition for leaf spring assembly and smooth specimen.

3.3. Fatigue Test Results

Figure 9 synthetically shows the relationship between fatigue load and life of leaf spring assembly and leaf spring material those are before- and after-shot peening. In case of leaf spring material, it does not show large difference between fatigue load and life at high load and short life region. But, it shows difference at low load and long life region near the fatigue limits.

In general, since actual applied load to leaf spring during LCV is running is much higher than fatigue limits, the compressive residual stresses of leaf spring generated in the process of shot peening make alleviation the tensile stresses generating from bending deformation under actual driving condition.

Table 3. Fatigue test conditions.

Condition	Contents	
	Spring ass'y	Smooth specimen
Control mode	Displacement	Load
Wave form	Sine	Sine
Frequency	0.2–3 Hz	5 Hz
Loading method	Reducing 10% from the maximum load	

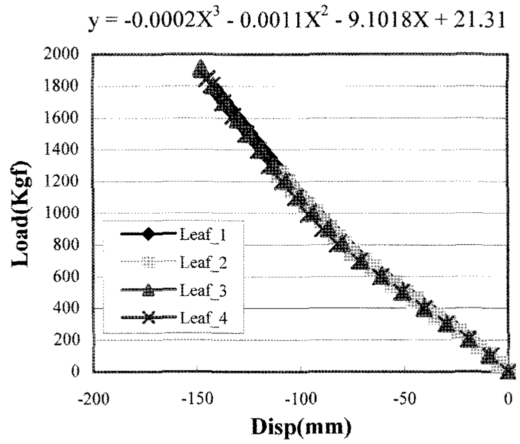


Figure 8. Relationship between load and displacement based on the data obtained through the proving ground tests.

Therefore, since degradation rate by fatigue will be increased according as bending deformation by external load is increased, shot peening effect about fatigue endurance will be inversely reduced. Actually, these cases are confirmed from some damage cases of vehicle service record by over weight or severe road conditions. To develop a new fatigue design method for leaf spring of the LCV, a new design criterion must be defined base on actual proving ground response. After that, it should be compared with the traditional leaf spring design method to confirm its reliability. Then we can propose new fatigue design method for leaf spring of the LCV.

From fatigue data on Figure 9, synthetic fatigue limit, that is defined as 10^6 cycles, of leaf spring assembly and leaf spring material was predicted as 6125N. So far, in order to design new leaf spring assembly for vehicles, fatigue load and life relation should be defined according to case by case. To do so, a lot of time and money for fatigue design of leaf spring have to be consumed. It is not economical and unreasonable.

Therefore, it is necessary to develop a new fatigue design method of leaf spring assembly that is improvable such problems. As shown in Figure 9, 3-point bending fatigue test results of simulated simple specimen show good agreement with the results of leaf spring assembly. It means that fatigue data obtained by 3-point bending fatigue tests for simulated simple specimens can be used as fatigue design criterion for leaf spring assembly. Furthermore, it is possible to attain saving cost and developing time to design of leaf spring assembly.

From Figure 9, relationship between fatigue load and life to design of leaf spring assembly can be formularized as follow;

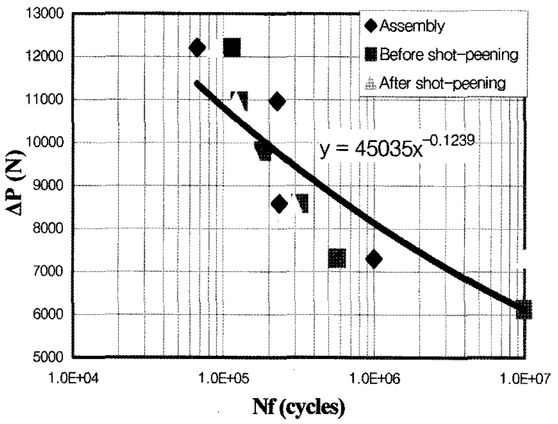


Figure 9. Fatigue test results of leaf spring assembly and 3 point bending specimen.

$$\Delta P = 45034.9\ N_f^{-0.1239}\ \text{N} \tag{1}$$

4. CONCLUSIONS

Using the actual road load response of leaf spring, the fatigue load-life relation of leaf spring was obtained through fatigue tests. 3-point bending specimen tests were also conducted to evaluate the effect of shot peening on the fatigue strength of leaf spring. From the above, following conclusions were summarized.

(1) Shot peening effects on fatigue strength of leaf spring material do not show large difference between fatigue load and life at high load and short life region. However, it is not negligible at low load and long life region near the fatigue limits.

(2) It was confirmed that fatigue data for the simulated 3-point bending specimen of leaf spring material could be used as a fatigue design criterion of leaf spring assembly. Their fatigue limit was predicted as 6,125 N.

(3) New fatigue design criterion and the test method for leaf spring assembly of LCV based on proving ground response have been proposed.

(4) The relationship between fatigue load and fatigue life to design of leaf spring assembly of LCV can be formularized as follow;

$$\Delta P = 45034.9\ N_f^{-0.1239}\ \text{N}$$

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