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Autofrettage of Fuel Injection Pipe

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Abstract—**In order to investigate the optimum conditions of the autofrettage process for the fuel injection pipe in diesel engine, different levels of autofrettage pressure, pressure rising time, pressure holding time, and repetition of autofrettage were applied. The autofrettage residual stresses in the fuel injection pipe were experimentally measured by using X-ray diffractometer. As the overstrain level increased, the magnitude of compressive tangential residual stress at the bore increased. It was found that the rising time to the autofrettage pressure, holding time at the autofrettage pressure, and repeated application of the autofrettage pressure had no significant influence on the residual stress distributions in the pipe.**

Keywords—**Fuel injection pipe, Autofrettage, Residual stress**

I. Introduction

For a thick-walled pressure vessel subjected to internal pressure, the largest tensile tangential stress occurs at the inside diameter. If the vessel is subjected to a pulsating internal pressure, then fatigue cracks usually originate at the inside surface and grow rapidly, resulting in final fracture. To prevent the failure of the thick-walled pressure vessel, an autofrettage process that produces favorable compressive tangential residual stresses at the bore of the vessel has been commonly employed [1, 2]. The compressive residual stress counteracts the tensile operating stress caused by the internal pressure, thus increasing the elastic strength of the pressure vessel. Therefore, the estimation of the residual stress distribution in the autofrettaged pressure vessel is very important for the accurate prediction of the elastic and fatigue strengths of the pressure vessel [3].

Recently, a common rail system in diesel engine fuel injection equipment has been developed in order to meet the future stringent emissions requirements and improve the fuel economy. The atomization by the electronic-controlled fuel injectors promotes combustion at all engine speeds, thus achieves reduced emissions and engine noise, and high fuel economy. Therefore, the common rail system requires maintaining high injection pressure for the fuel piping. In this research, the thick-walled fuel injection pipes in the common rail diesel engine system were autofrettaged with different levels of autofrettage pressure, pressure rising time, and number of repetition. In order to find an optimum autofrettage procedure for the fuel injection pipe, residual stresses in the autofrettaged pipes were measured experimentally and compared to the analytical results.

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II. Autofrettage Pressure and Residual Stress Distribution

In order that the fuel injection pipe subjected to the high internal pressure has sufficient elastic and fatigue strengths, the tangential tensile stress at the bore of the thick-walled fuel injection pipe should be quite lower than the yield strength of the material. This can be attained by inducing the tangential compressive residual stress at the bore, i.e. autofrettage process, since the residual compressive stress compensates for the operating tangential stress. The autofrettage is a metal forming process, applying a hydrostatic pressure high enough to produce the plastic deformation in the pipe. Releasing the pressure generates the non-uniform elastic recovery and thus induces residual stresses through the thickness of the pipe.

A thick-walled pipe considered in this research was developed for the fuel injection piping in the common rail diesel engine system. The pipe was subjected to a pulsating internal pressure of 105 MPa during operation. Inside and outside radii of the pipe were 14 mm and 27 mm, respectively. The pipe was made of SCM440 steel with yield and tensile strengths of 1018 MPa, and 1109 MPa, respectively. The radial and tangential stresses due to internal pressure, P_i, can be represented by the following Lamé equation [4],

$$\sigma_r = \frac{P_i a^2}{b^2-a^2}\left[1-\frac{b^2}{r^2}\right] \quad \sigma_\theta = \frac{P_i a^2}{b^2-a^2}\left[1+\frac{b^2}{r^2}\right] \qquad (1)$$

where a, b are inner and outer radii of the pipe, respectively. Assuming the elastic-perfectly plastic behavior and von Miese yield criterion for the pipe material, the autofrettaged pressure, P_u, for a partially autofrettaged tube as shown in Figure 1 can be obtained as follows [2],

$$P_u = \frac{\sigma_y}{\sqrt{3}}\left[\left(1-\frac{\rho^2}{b^2}\right)+2ln\frac{\rho}{a}\right] \qquad (2)$$

where the radius, ρ corresponds to the elastic-plastic boundary during the autofrettage pressure loading. The level of autofrettage is expressed by the percent overstrain(%OS), representing the ratio of the plastically deformed thickness to the total thickness of the pipe.

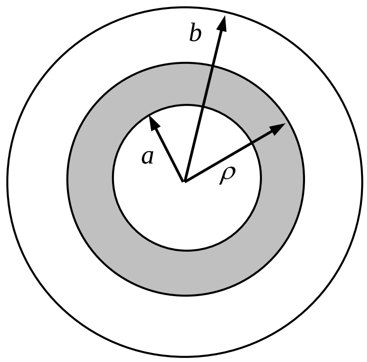

Figure 1. Autofrettaged thick-walled pipe.

Three different levels of pressure such as 604 MPa, 535 MPa, and 500 MPa were applied to the pipe for autofrettage, which were corresponding to the theoretical autofrettage levels of 26%OS, 14%OS, and 9%OS from (2), respectively. The autofrettage pressure as a function of overstrain level can be shown in Figure 2. From (2), a theoretical autofrettage pressure of 773 MPa can be obtained for the case of 100%OS.

Tangential residual stresses in a partially autofrettaged pipe can be calculated by assuming the elastic-perfectly plastic material behavior, plane strain condition, and von Mises yield criterion [1],

$$\sigma_\theta = \frac{2}{\sqrt{3}}\sigma_y\left\{\frac{a^2}{b^2-a^2}\left(1+\frac{b^2}{r^2}\right)\left[\frac{\rho^2-b^2}{2b^2}-ln\frac{\rho}{a}\right]+\left[\frac{\rho^2+b^2}{2b^2}-ln\frac{\rho}{r}\right]\right\}, for\ a \le r \le \rho$$

$$= \frac{2}{\sqrt{3}}\sigma_y\left\{\frac{a^2}{b^2-a^2}\left(1+\frac{b^2}{r^2}\right)\left[\frac{\rho^2-b^2}{2b^2}-ln\frac{\rho}{a}\right]+\left[\frac{\rho^2+b^2}{2b^2}-ln\frac{\rho}{r}\right]\right\}, for\ \rho \le r \le b \quad (3)$$

Residual stress distributions in an autofrettaged fuel injection pipe with yield strength of 1018 MPa are shown in Figure 3. The magnitude of compressive tangential residual stress at the bore increases as the level of autofrettage increases, approaching the value of yield strength for fully autofrettaged pipe as shown in Figure 4.

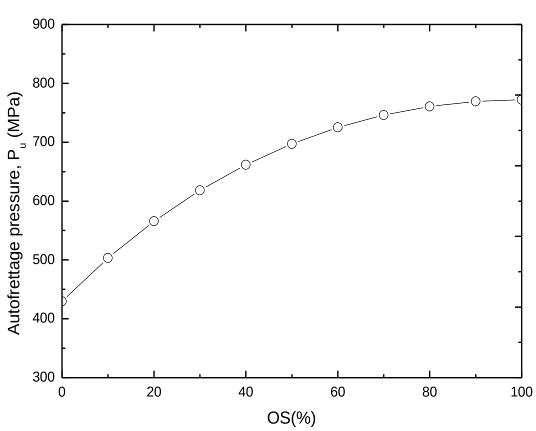

Figure 2. Autofrettage pressure for different overstrain levels.

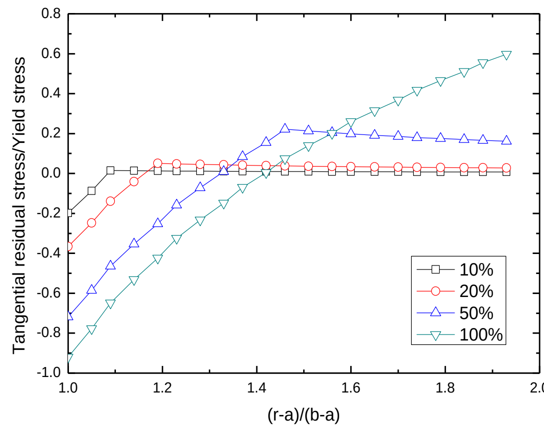

Figure 3. Theoretical tangential residual stress distributions in an autofrettaged pipes.

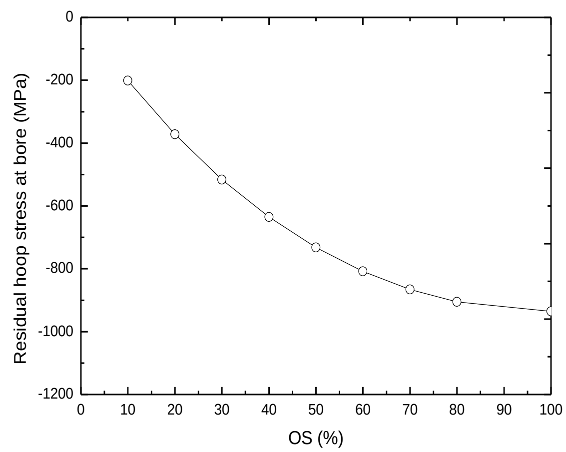

Figure 4. Tangential residual stress versus overstrain level in autofrettage pipes.

III. Residual Stress Measurement of Autofrettage Pipe

Since the deformation behavior of material depends on the loading rate, the time to reach the autofrettage pressure and the time to hold the pressure can have influence on the residual stress distributions in the autofrettaged pipes. In order to investigate the effects of the autofrettage process variables and to find an optimum procedure in the pipe autofrettage, the several different values of pressure rising and holding times were applied to the autofrettage, including the repetition of autofrettage.

Residual stresses in the pipe induced by the autofrettage were determined experimentally using X-ray diffraction method. Specimens with a ring shape were cut perpendicular to the longitudinal axis of the autofrettaged pipe and listed in Table 1. The cutting surface was electro-polished and tangential residual stresses along the thickness of the pipe in the radial direction at an interval of 0.5 mm distance. Measured tangential residual stress distributions are shown in Figure 5, indicating that compressive residual stresses ranging from -70 MPa to -260 MPa at the bore and from -100 MPa to 280 MPa at the outside of the pipe.

Table 1. Conditions for injection pipe autofrettage.

Specimen ID	Autofrettage pressure (MPa)	Pressure rising time (min.)	Pressure holding time (min.)	Repetition of autofrettage
S1	604	2	0	1
S2	536	2	0	1
S3	500	2	0	1
S4	604	5	0	1
S5	604	5	0	1
S6	604	2	5	1
S7	604	2	5	1
S8	604	2	0	3
S9	604	2	0	3

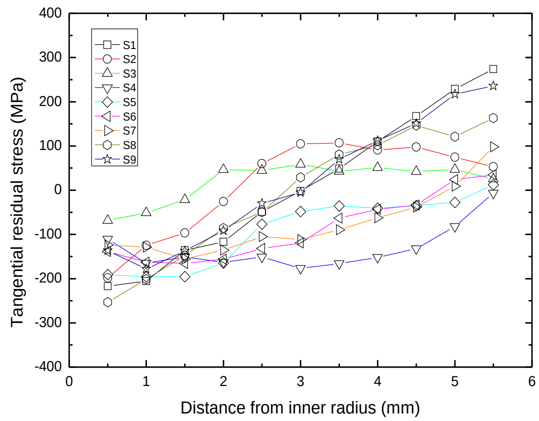

Figure 5. Measured tangential residual stresses in autofrettaged fuel injection pipes.

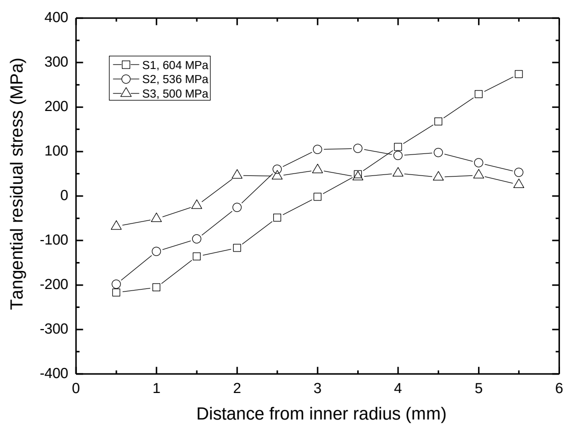

Figure 6. Tangential residual stresses for different autofrettage pressures in injection pipes.

Table 2. Comparison of theoretical and experimental residual stresses at the bore of the autofrettaged injection pipes.

Autofrettage pressure (MPa)	OS (%)	Tangential residual stresses (MPa)	
		Theory	Experiment
604	26	-462	-380
535	14	-276	-250
500	9	-180	-120

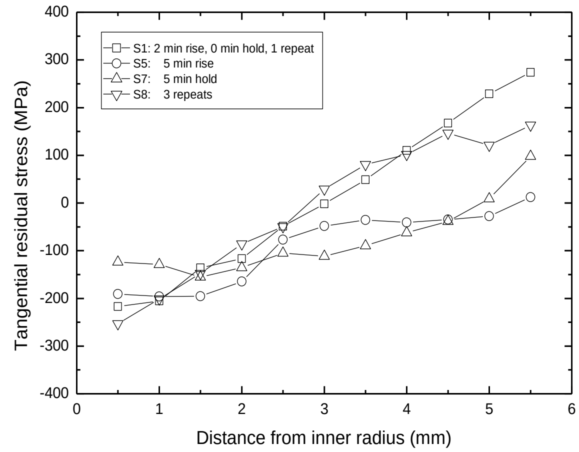

Figure 7. Tangential residual stresses for different autofrettage processes at a pressure of 604 MPa.

Residual stress distributions in pipes with different autofrettage pressures of 604 MPa, 535 MPa, and 500 MPa are shown in Figure 6. The higher the level of autofrettage pressure, the larger the magnitude of the compressive residual stresses near the bore. Since the residual stress at the inside surface could not be measured, the value at the bore was determined by extrapolation. Theoretical and measured residual stresses at the bore are listed in Table 2. It was found that the measured values were lower than the theoretical values, and the difference was attributed to the Bauschinger effects by reverse yielding. The measured compressive residual stress at the bore for the pressure of 535 MPa was 250 MPa, which was larger than the tangential stress of 182 MPa due to operating pressure of 105 MPa in the fuel injection pipe, implying the improved elastic strengths of the pipe due to autofrettage. Effects of the pressure rising time, holding time, and repetition on the residual stress distributions are shown in Figure 7 for the autofrettage pressure of 640 MPa. No significant effect was observed.

IV. Conclusions

To ensure the elastic strength of the high pressure fuel injection pipe used for common rail diesel engine system, optimum conditions of autofrettage process were investigated. As the overstrain level increased, the magnitude of compressive tangential residual stress at the bore increased, resulting in the tangential compressive autofrettage residual stress which compensated for the tangential stress due to operating pressure. It was found that the rising time to the autofrettage pressure, holding time at the autofrettage pressure, and repeated application of the autofrettage pressure had no significant influence on the residual stress distributions in the pipe.

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