A Report of Engin-X Experiment and FEA Investigation onto the ISIS Thick Walled Aluminium High Pressure Vessels

Compiled by Yanling Ma, Shu Yan Zhang and Beth Evans on 30th June 2011

1. Introduction

In order to carry out optimised safe design of any autofrettaged thick-walled cylindrical high pressure vessels for the JRA project and for the ISIS instrument use, the information of the specific positions of the elastic plastic interfaces determined experimentally is vital. The Engin-X instrument of ISIS has the capability [1] of determining such features via measuring the lattice parameters of autofrettaged materials. Several aluminium vessels subjected to different autofrettage pressure levels were therefore prepared and measured experimentally. The experimental results of residual elastic microstrains were obtained, by which the positions of elastic plastic interfaces for different vessels were determined. Using these vital information, a design guideline was formed, i.e., it (the design guidline) can clearly tell a designer what should be the maximum allowable autofrettage pressure and where the position of elastic plastic interface of a thick walled high pressure vessel should be etc.. So that not only the detrimental reverse yielding can be avoided, but also the ultilisation of material strength of a high pressure vessel can be maximised. More importantly, it can lead to the safe design and particularly the safe use of high pressure vessels anywhere inside or outside of the ISIS facility. It is, therefore, the necessity and importance of the Engin-X experiment conducted recesently.

2. Materials and Equipment

Equipment used for the experimental investigation is the ISIS Engin-X instrument as mentioned previously. Materials selected for the investigation is Aluminium 7075 T6 due to its high strength, low cost and neutron compatibility. Details of the material properties (including material testing raw data, report and microstructure examination results) can be found in Appendix 1a, 1b and 1c, respectively. The material properties used in the FEA analysis are listed in Table 1.

Table 1 Mechanical properties of Aluminium 7075 T6/T6511

Yield strength	Tensile strength	Elastic modulus	Poisson's ratio
570 MPa	640 MPa	70 GPa	0.33

It should be noted that (1) material strengths indicated in Table 1 are the material longitudinal behaviour; (2) minimum value of the material properties are listed in Table 1.

Using the above material, 6 samples, which have the modified geometries, i.e. the utilisation of internal slope transition structure of the ISIS standard aluminium thick-walled high pressure gas vessels (refer to Figure 1), were prepared. The major dimensions of the samples and the autofrettage pressure levels subjected by the samples are shown in Table 2.

Table 2 Information of the samples

Sample Number	1	2	3	4	5	6
Autofrettage Pressure (MPa)	0	200	400	500	600	700
Outer and major inner diameters (mm)						
Each of the 6 samples has the identical outer diameter of 28mm and major inner diameter of 7mm, respectively, as depicted in Figure 1.						

Note: (1). Sample 3 was a re-use of sample 2, i.e. after the release of 200MPa, the cell was re-pressurised to 400MPa; (2). Sample 4 was a re-use of sample 1.

The position of the Engin-X measurement is presented in Figure. 1 and a whole picture of a typical high pressure gas vessel (without slope structure adopted) assembly is shown in Fig. 2.

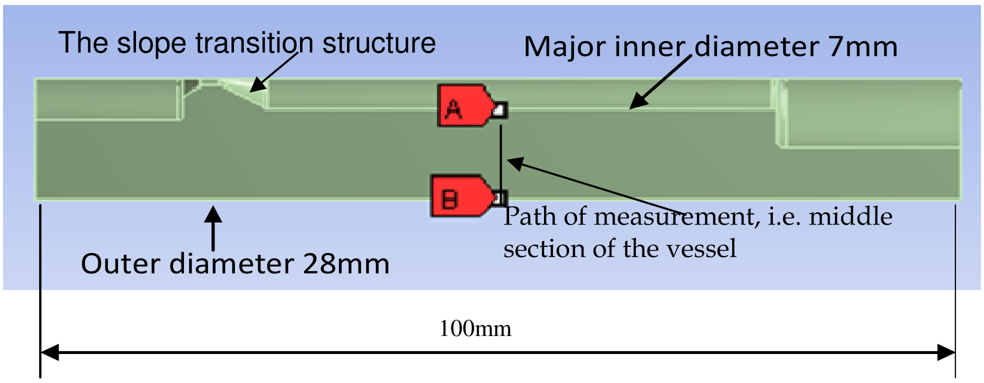


Figure 1 Position of Engin-X Measurement

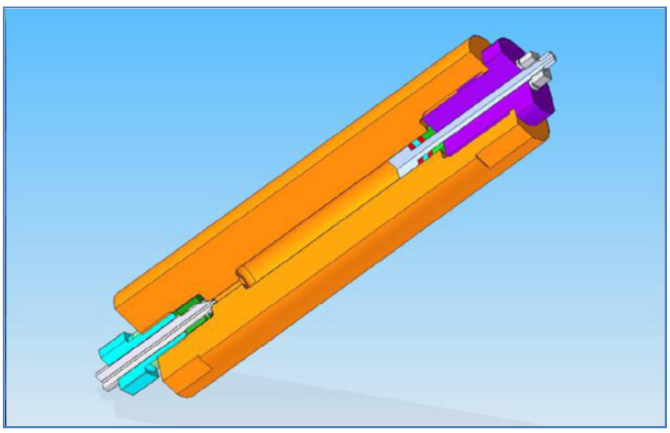


Figure 2 The assessmbly of a typical high pressure vessel (without slope transition structure adopted

It should be pointed out that the autofrettage pressure levels indicated in Table 2 were determined based on some hand calculations initially (those initial values obtained are not shown in this report). Some of the imperial formulae used in the initial hand calculations can be found in Appendix 5 of formulae (1), (3) and (4), where the reverse yielding and transverse material properties were not considered at that stage. Following some experiences gained during sample preparation (burst of one sample) and particularly after obtaining the measured results (in which the reverse yielding was revealed) from the first Engin-X experiment, it was agreed that the maximum autofrettage pressure levels need to be revised. So that more useful results could be obtained from the next Engin-X experiment (May 2010), hence, the final autofreattge pressure levels shown in Table 2.

3. Results and discussions

The above 6 samples prepared under different autofrettage pressure levels were measured with the ISIS Engin-X instrument. Residual elastic microstrains, along the vessel wall thickness (from point A to B refer to Figure. 1) for all 6 samples were obtained. Two typical experimental and FEA results are compared in Figures 2 to 3 for the samples subjected to the autofrettage pressure levels of 500MPa and 600MPa, respectively.

Prior to the discussions of the results obtained, it should be pointed out that although the real vessel's wall thickness is 10.5mm as shown in Figure. 1, the data for both FEA and experimental results shown in Figures 2 to 3 were only available for a measured vessel wall thickness of 9.5mm. This is because the FEA and particularly the Engin-X experiment excluded 0.5mm from both the inner surface and outer surface of the vessel wall thickness to ensure the experimental result accuracy, due to the 1x1 mm^2 beam size. In addition, based on the experimental results and MIL-HDBK-5H standard [2], the deduced transverse tensile yield strength of 460MPa (which is about 80% of the material longitudinal yield strength) was used by the FEA models.

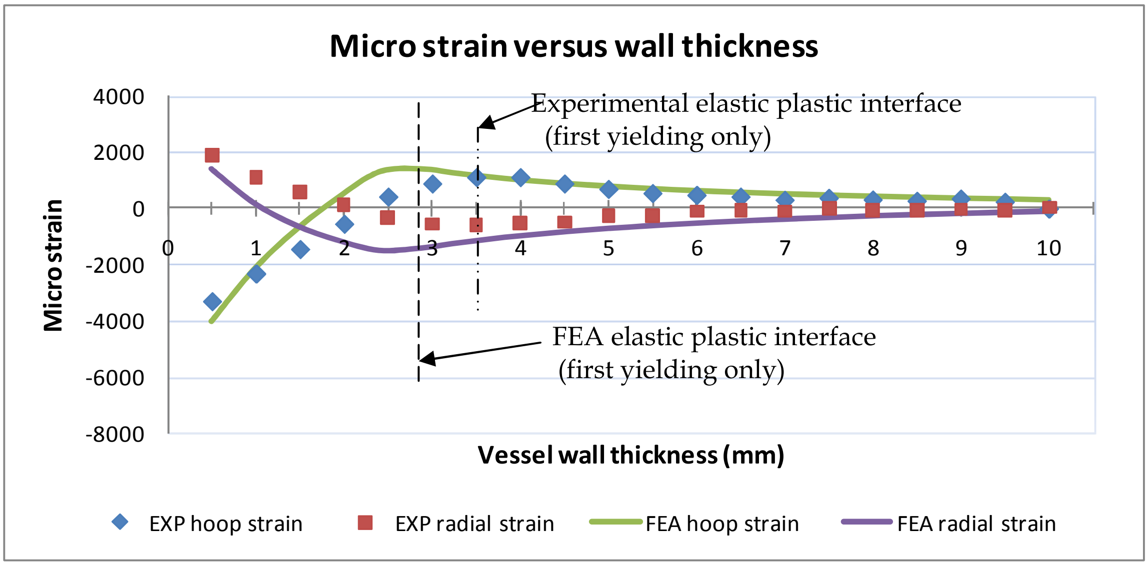


Figure 2 The results of under 500MPa autofrettage pressure

It can be seen form Figure 2, the experimental residual hoop elastic microstrain shows a continuous increase from the measured inner surface (with a value of -3308) of the vessel to a peak value of 1067 microstrain at about 3.5mm depth from the vessel's actual inner surface. After the peak value point, the residual hoop elastic microstrain changed its slope direction and then the microstrain value decreases gradually as the vessel wall thickness increases until the maximum measured vessel wall thickness of 10mm. The location of the slope direction change at the peak value of the residual elastic hoop microstrain revealed the specific position of the elastic plastic interface of the high pressure aluminium vessel. In another word, after the aluminium vessel autofrettaged with 500MPa pressure, the plastic region of the vessel is found on the left of the peak strain value and the elastic region is on the right side of the peak strain value. This position of the elastic plastic interface is also called the first yielding location (as there is only one residual elastic hoop microstrain slope direction change). Such results also verified that, for this specific vessel geometry made of this specific material, the safe allowable autofrettage pressure is 500MPa, which ensures the autofrettaged vessel works elastically in its subsequent use.

Similarly, Figure 3 shows the variation of residual elastic hoop microstrain along the wall thickness of the aluminium vessel. Clearly, with the increase of autofrettage pressure from 500MPa to 600MPa, the experimental results indicated not only a increase in thickness of plastic region from 3.5mm (shown in Figure 2) to 5.5mm in this case (refer to the left side of the peak strain value at the first yielding interface), but also a secondary slope direction change of the residual elastic hoop microstrain, which is near the inner surface of the vessel. This secondary slope direction change presented the occurrence of reverse yielding, also called Baushinger effect [3-4], which restrains the vessel's subsequent elastic use and need to be avoided.

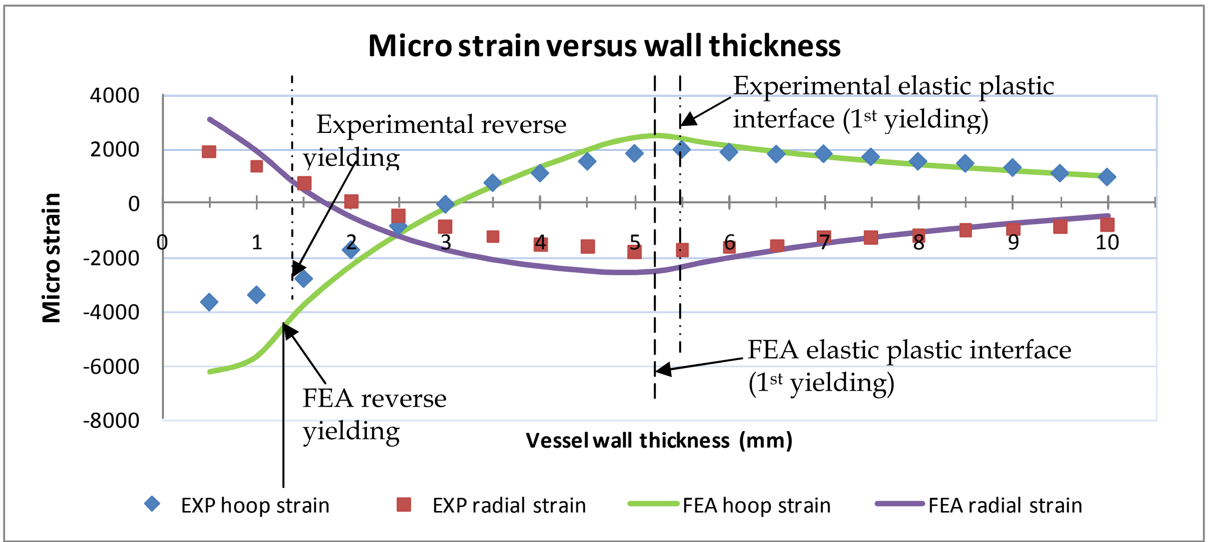


Figure. 3 The results under 600MPa autofrettage pressure

It is therefore said that for the identical aluminium vessel geometry, after it is autofrettaged with 600MPa, the vessel is not safe to use due to the reverse yielding.

The above experimental results also verified the FEA analysis conclusions made in 2009 [5], i.e., the plastic deformation depth from the inner wall surface of the vessel should not be bigger than 3.5mm for the issued vessel geometry (compare Figure 2 and Figure 3). The reason for this is that, "In general, the autofrettage pressure should not exceed that needed to take the diameter of the plastic/elastic boundary to the geometric mean of the outside and inside diameters of the vessel." [6]. Similar requirement was also issued as "In most pressure vessel operations, it is desirable to leave the cylinder in a completely elastic state after autofrettage rather than with a reverse-yielded inner core." [7]. For ensuring the same goal, another resource also stated that: "The maximum allowable autofrettage pressure is then given as that which will produce yielding to the geometric mean radius $Rp = \sqrt{\mathrm{R1} \times \mathrm{R2}}$." [8], where R_p/$Ø_p$ is the geometric mean radius/diameter of the high pressure vessel (in this case plain cylinder). R_1 and R_2 are the inner and outer radius of of the plain cylinder, respectively. Hence, for K value 4, the maximum radius of plastic/elastic boundary will be $Rp = \sqrt{3.5 \times 14}$ =7mm and therefore the plastic deformation depth from inner surface of the vessel should be $R_p - R_1$ =7-3.5=3.5mm. Both experimental and FEA results also indicate that the results obtained from the simplified hand calculation seem less conservative.

It also should be noted that the material used in the FEA model [5] at that time was Beryllium Copper 25HT, rather than aluminium 7075T6/T6511 in this investigation. Literature [3], however, indicates that reverse yielding (the Bauschinger effect) seems not to be dictated by different materials' yield strengths. Also although the FEA results produced at that time (April 2009) did not show any sign of reverse yielding, which was because the use of ANSYS workbench was unable to detect reverse yielding. That was why ANSYS classic was employed subsequently to include the occurrence of reverse yielding as depicted in Figures 2 to 3 and Appendix 2. A detailed investigation about reverse yielding (Bauschinger effect) in a high strength steel can be viewed in literature [3]. A brief description about it is also presented in Appendix 3.

In addition, it was also observed that, when autofrettage pressure increases from 600MPa to 700MPa, as expected, not only larger plastic region (after the first yielding), but also server reverse yielding resulted from. Detailed results of the sample under such higher autofrettage pressure level can be found in Appendix 2. On the other hand, when the autofrettage pressure level is lower than 500MPa as shown in Table 2, either only first yielding occurred with a smaller plastic region (for 400MPa) or there was no first yielding at all (for 0 and 200MPa) as expected. These results are also presented the Appendix 2.

4. Validation of experimental results

To validate the experimental results, two criteria were used to check the experimental results obtained. One is the use of strain error bar and another is the use of peak width. The strain error bar uses a specified acceptable strain error value to check the accuracy of the strain value measured. In this experimental investigation, a strain error bar value of about 80 microstrains is acceptable for the samples subjected to the autofrettage pressure levels of 600MPa or above. For the rest of samples, i.e., those ones subjected to the autofrettage pressure levels of 500MPa or below, a strain error bar value of about 50 microstrains is acceptable. Using this criterion, all the residual elastic microstrains measured (either for radial or hoop) were checked. The results showed that all the residual microstrains measured have met the prescribed strain error bar criterion. One out of six of the strain error bar check results is shown in Figure 4 for the sample autofrettaged at 600MPa.

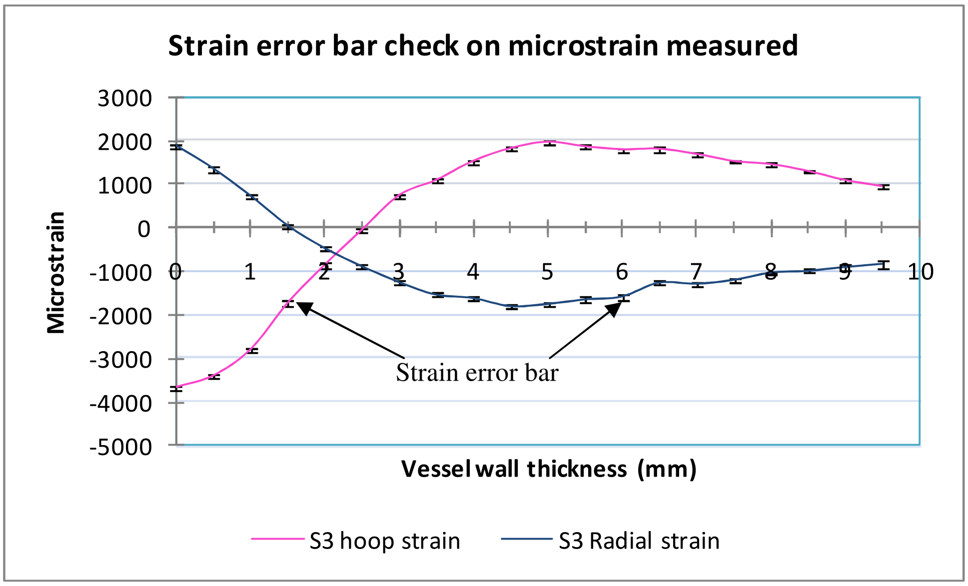
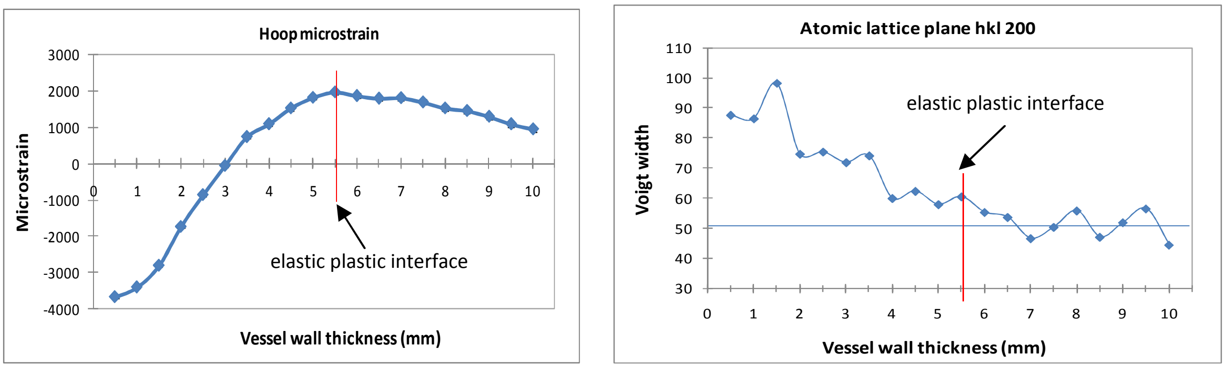


Figure 4 Error bar check (80 microstrains) on the microstrain measured of sample subjected to 600MPa autofrettage pressure

As shown in Figure 4, the microstrain error was so small that the error bar was not visible, if the marks of presenting measured residual elastic microstrains (like the ones in Figures 2 to 3) were not removed and if the line thickness of the curve of plotting measured residual microstrain was not thinned. In one word, all the strain error values produced during Engin-X experiment are smaller than the prescribed value of 80 microstrains in this case. In fact, similar results of strain error bar check were also obtained for all the residual microstrains measured on all the aluminium vessels subjected to all the different autofrettage pressure levels. Particularly the most valuable parameter, namely residual elastic hoop microstrains, have met all the strain error check criteria. Also although there was no any autofrettage effect involved in the vessels subjected to the pressure levels of 200MPa and 0 MPa, all of the strain error bar check results, including the last two, are presented in Section 1 of Appendix 4.

It is well-known that the diffraction peak shape changes when plastic deformation occurs. The main contributions to peak broadening includes particle size broadening, dislocations, stacking faults, microstrain broadening and steep strain gradients. Generally, diffraction peaks get broader when crystal slip occurs, due to the increased root mean square (RMS) microscopic strain distribution within sampling volumes caused by the presence of lattice distortions caused by dislocations. It is useful to carry out peak broadening analysis of diffraction data to detect the onset of plastic deformation. [9] In this project, the diffraction peak width method uses the variation of peak width to detect the elastic plastic interface, i.e., when the overall trend of peak width is varying (either increasing or decreasing) along the measured material thickness, this indicates the existence and variation of plastic strain, therefore the discovery of plastic region. In contrast, when the overall trend of peak width is constant, this declares the non existence and non variation of plastic strain, therefore the discovery of elastic region. Based on this criterion, the elastic plastic interfaces determined via residual elastic hoop microstrains were checked. The result for the sample of subjected to 600MPa autofrettage pressure, as an example, is dipicted in Figure 5.



(a) Elastic plastic interface determined via residual elastic hoop microstrain

(b) Elastic plastic interface determined via peak width

Figure 5 Peak width check of elastic plastic interface determined via residual elastic hoop microstrain for sample of subjected to 600MPa autofrettage pressure

Figure 5 (a) shows the elastic plastic interface determined via residual elastic hoop microstrain, which is at about 5.5mm from the vessel's actual inner wall surface. The result of using peak width method is demonstrated in Figure 5 (b). Clearly, the peak width (as a whole) was decreasing from the measured inner wall surface of the vessel with a peak width value of about 90 to about 5.6mm from the actual vessel's inner wall surface with a peak width value of about 60. Therefore the plastic region (due to autofrettage process with 600MP for the investigated vessel) is found on the left side of the red bar shown in Figure 5 (b) with a depth of about 5.6mm. After the 5.6mm vessel wall thickness point, the overall peak width variation is constant with a peak width value of about 52. This is, of course, the indication of the elastic region for the same vessel. Therefore, the position of the elastic plastic interface of 5.5mm from the vessel inner wall surface determined via residual elastic hoop microstrain agreed very well with the position of elastic plastic interface of 5.6mm from the same inner wall surface determined via peak width criterion. Similar results were also obtained for all the other autofrettage pressure levels, which can be reviewed in Section 2 of Appendix 4.

5. Conclusions

Form the above discussions, following conclusions can be drawn:

1. The Engin-X experiment determined the residual elastic microstrains for all the autofrettaged and non-autofrettaged thick walled aluminium pressure vessels, which was validated by strain error bar check with success;

2. The specific positions of the elastic plastic interfaces were determined via the residual elastic hoop microstrains measured. The interface position was also confirmed by peak width criterion;

3. Good agreement between FEA and experimental results were attained, following the FEA models conditioned with the experimental results;

4. The experimental results also verified the FEA analysis conclusion made in 2009 and the suggestions made by High Pressure Safety Code;

5. Both experimental and FE results also indicate that the results obtained from the simplified hand calculation seem less conservative;

6. Both the experimental and FEA results are reliable and can be used to carry out the optimised safe design and safe use based on a maximum utilisation of material strength.

5. Reference

[1] S.Y. Zhang, E. Godfrey et.al, High-tech composites to ancient metals, Materials today, NEUTRON SCATTERING SPECIAL ISSUE, ISSN: 1369 7021 © Elsevier Ltd 2009, pp78-84.

[2] MIL-HDBK-5H standard, 1 December 1998, pp 3-345 to pp 3-379.

[3] R.V.Milligan, W.H. Koo and T.E. Davidson, The Bauschinger Effect in a High-Strength Steel, Transactions of the ASME, June 1966, pp480-488.

[4] A.M. Venter, R.R. de Swardt and S. Kyriacou, Comparative measurements on autofrettaged cylinders with large Baushinger reverse yielding zones, Journal of strain analysis, Vol. 35, No. 6, 2000, pp459-469.

[5] Y. Ma, A FEA report for applying autofrettage technology on plain cylinders, Compiled on 27th July 2009, pp 46-49.

[6] High Pressure Safety Code, High Pressure Technology Association, 1977 (RAL 1983), pp 29-30.

[7] High pressure technology – volume 1 – chapter 7 – high pressure containment in cylindrical monobloc vessels, p229-251.

[8] E. J. Hearn, Mechanics of Materials, Int. Series on Materials and Technology, Vol. 19, 1985, pp. 516-519.

[9] S.Y. Zhang (2008), High Energy White Beam X-ray Diffraction Studies of Strains in Engineering Materials and Components, D.Phil thesis, University of Oxford

6. Appendixes

(1) Appendix 1a_Material testing raw data

(2) Appendix 1b_Material testing report

(3) Appendix 1c_Material microstructure examination report

(4) Appendix 2_All Experimental and FEA results

(5) Appendix 3_A brief description about reverse yielding

(6) Appendix 4_Strain error and Voigt width check results

(7) Appendix 5_Some formulae used initially for HP cells for the JRA project