Final Report

Numerical Prediction of Residual Stress and Deformation of Cannon Tubes

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13. ABSTRACT (Maximum 200 Words)
An experimental program involving uniaxial testing of candidate gun steels was undertaken at Benét Laboratory. One striking feature is a very significant reduction in elastic modulus during load reversal. These data were then fitted numerically using a new variant of the non-linear kinematic hardening model. Numerical fits to the uniaxial behavior were incorporated into a non-linear numerical stress analysis program. Residual stress profiles for each of the candidate gun steels were then calculated; because of the combined influence of strain hardening, unloading modulus and Bauschinger effect the optimum residual stress field is not provided by the strongest material. Residual bore hoop stress values were fitted using a numerical procedure. These were employed in calculating predicted pressures for the re-yielding of tubes subjected to high pressure after autofrettage. Additional work, beyond contract requirements, was undertaken as follows:
(i) The behavior of a current gun steel was used to determine, with Bauschinger effect, residual stresses in a swage-autofrettaged gun tube.
(ii) An initial study of the mechanics of a specific wear process was undertaken.
(iii) A simple procedure was devised to test the general assumption that the Bauschinger effect is isotropic. Using two uniaxial tests, undertaken by Mr. E Troiano of Benét Laboratory, it has been demonstrated that the Bauschinger effect exhibits significant anisotropy.

14. SUBJECT TERMS
Residual Stress, Autofrettage, High Pressure, Cannon Tubes

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Problems Studied

The following problems were studied, in full satisfaction of the contract requirements:

1. Characterization of candidate gun steels via numerical fitting of uniaxial test data
2. Numerical determination of residual stresses in autofrettaged gun tubes manufactured using the candidate steels
3. Numerical fitting of results from (2) above for use by designers
4. Results of (3) above employed in prediction of re-yielding behavior of autofrettaged tubes

In addition three other problems were addressed during the period of the contract:

5. Prediction of residual stresses in a swage autofrettaged gun tube and comparison with equivalent stresses in a hydraulically autofrettaged tube
6. Preliminary study of possible coating erosion mechanism in a gun tube
7. Preliminary investigation to identify anisotropic behavior in a material which exhibits the Bauschinger effect

Abstract

An experimental program involving uniaxial testing of a range of candidate gun steels was undertaken at Benét Laboratory. One striking feature of this uniaxial behavior is a very significant reduction in elastic modulus during load reversal. These data were then fitted numerically using a new variant of the non-linear kinematic hardening model. Numerical fits to the uniaxial behavior were incorporated into a numerical program. Residual stress profiles for each of the candidate gun steels were then calculated; because of the combined influence of strain hardening, unloading modulus and Bauschinger effect the optimum residual stress field is not provided by the strongest material.Residual bore hoop stress values were fitted, for use by designers, using a numerical procedure. These, in turn were employed in calculating predicted pressures for the re-yielding of tubes subjected to proof testing or high firing pressure after autofrettage.

Additional work, beyond the requirements of the contract, was undertaken as follows:
(i) The behavior of a current gun steel was used to determine, with Bauschinger effect, residual stresses in a swage-autofrettaged gun tube.
(ii) An initial study of the mechanics of a specific, potentially crucial, wear process was undertaken.
(iii) A simple experimental procedure was devised to test the general assumption that the Bauschinger effect is isotropic. Using only two uniaxial tests, undertaken by Mr. E Troiano of Benét Laboratory, it has been demonstrated that the Bauschinger effect exhibits significant anisotropy.

Definition of Terms

Autofrettage: the process of applying pressure or displacement to the bore of a gun tube during manufacture such that the tube material yields outwards from the bore to a given radius. The tube then 'locks in' advantageous residual stresses following removal of applied pressure or displacement
*Overstrain:* the proportion of the wall thickness of a gun tube within which yielding occurs during autofrettage.
Bauschinger effect: the non-linear behavior of a material when subjected to compressive loading following prior tensile plastic strain.

Problem Descriptions and Important Results

1. Characterization of candidate gun steels via numerical fitting of uniaxial test data

An experimental program involving uniaxial testing of a range of candidate gun steels was undertaken under the supervision of Mr. E Troiano of Benét Laboratories. For each steel these tests involved tensile loading to a defined maximum tensile plastic strain, followed by reversed loading into the compressive regime. One striking feature of this uniaxial behavior is a very significant reduction in elastic modulus during load reversal.
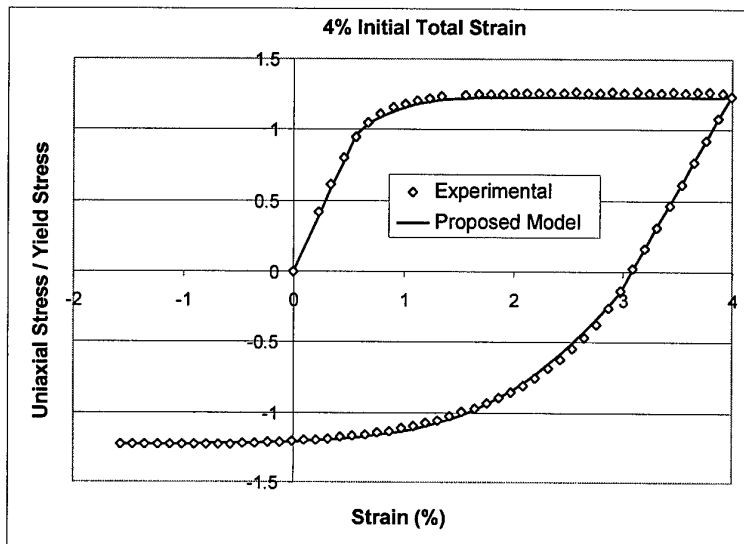
Figure 1 : Experimental Uniaxial Stress-Strain Data Compared with Fitting to proposed equations. 4% Total Initial Strain, HY180 steel.

These data, covering a range of maximum tensile plastic strains, were then fitted numerically A new variant of the non-linear kinematic hardening model was formulated which accommodates both non-linear and linear strain hardening during initial tensile loading. The model also incorporates the reduced elastic modulus during initial load reversal and the Bauschinger effect, as a function of prior tensile plastic strain, during

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the non-linear compressive loading phase. The model is shown to fit experimental data from a total of five candidate gun steels. These data may be used as an equivalent stress input to stress analyses of tubes and other components manufactured using the candidate steels. Specifically they are employed in subsequent work to predict residual stresses and fatigue lifetimes for autofrettaged tubes manufactured from the candidate steels. A typical example of the effectiveness of the numerical fitting procedure is shown in Figure 1.

Reference [1] has been submitted for presentation at the conference 'Gun Tubes 2002', Oxford, England, September 2002 and will then be considered for publication in the ASME Journal of Pressure Vessel Technology.

2. Numerical determination of residual stresses in autofrettaged gun tubes manufactured using the candidate steels

An existing numerical program, 'HENCKY', which models autofrettage pressurization and subsequent depressurization was completely revised, increasing the number of degrees of freedom by a factor of 25. Numerical fits to the uniaxial behavior, obtained as described in (1) above, were then incorporated into program 'HENCKY'. Residual stress profiles for each of the five candidate gun steels were then calculated for the full range of possible autofrettage overstrains. Figure 2 shows a typical variation of (compressive) bore hoop stress as a function of overstrain for a tube of radius ratio 2.

The complexities of strain hardening and reduced modulus during unloading produce some unexpected effects. The steel with the highest yield strength can, at a given overstrain, produce hoop residual stresses which are less compressive and therefore less desirable than an alternative, and more conventional, lower strength steel.

Reference [2] has been submitted for presentation at the conference 'Gun Tubes 2002', Oxford, England, September 2002 and will then be considered for publication in the ASME Journal of Pressure Vessel Technology.
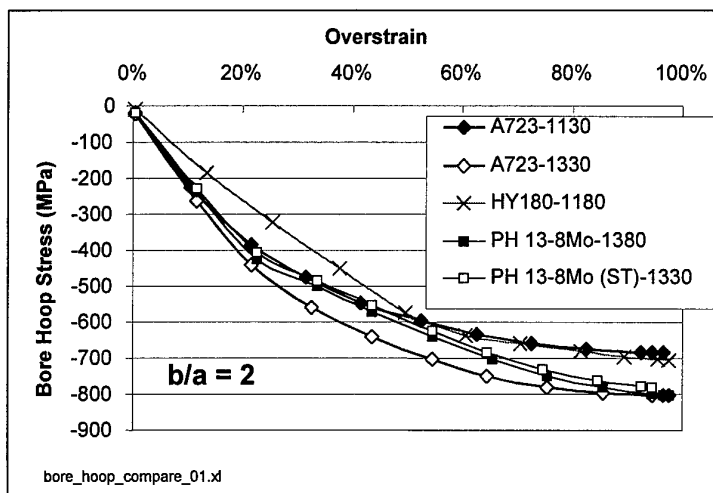

Figure 2 : Bore Hoop Stress Versus Overstrain, b/a = 2, all candidate steels.

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3. Numerical fitting of results from (2) above for use by designers

Residual stress profiles for each candidate steel, characterized via the value of residual hoop stress at the bore, were fitted using a numerical procedure which is a simple extension of that developed previously, reference [3]. These results are also presented in reference [2].

4. Results of (3) above employed in prediction of re-yielding behavior of autofrettaged tubes

Residual stress profiles from (3) above were employed in calculating predicted pressures for the re-yielding of tubes subjected to proof testing or high firing pressure after autofrettage. These calculations agreed with the experimentally measured yield pressure to within 3-5 % as illustrated in Figure 3 for a radius ratio of 1.88. Calculated yield pressure was found to be insensitive to the value of axial residual stress, since it is typically the intermediate value in the Von Mises yield criterion. This method for calculating yield pressure is proposed as a design procedure for cannons and other pressure vessels and has important implications relating to the definition of safe maximum pressure (SMP).
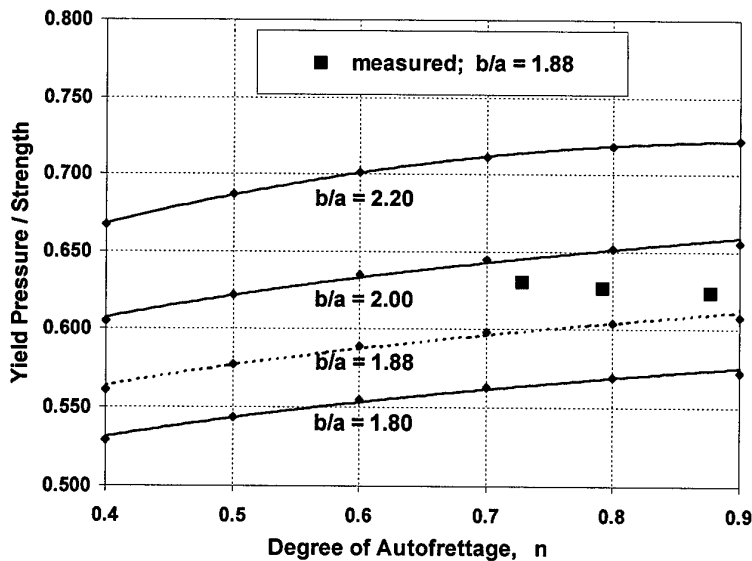
Figure 3 : Yield pressure design curve for A723 steel pressure vessels; for yield Strengths from 1000 – 1200 MPa

Reference [4] is to be presented at ASME Pressure Vessels and Piping Conference, Vancouver, Canada, August 2002 and will be submitted to ASME Journal of Pressure Vessel Technology.
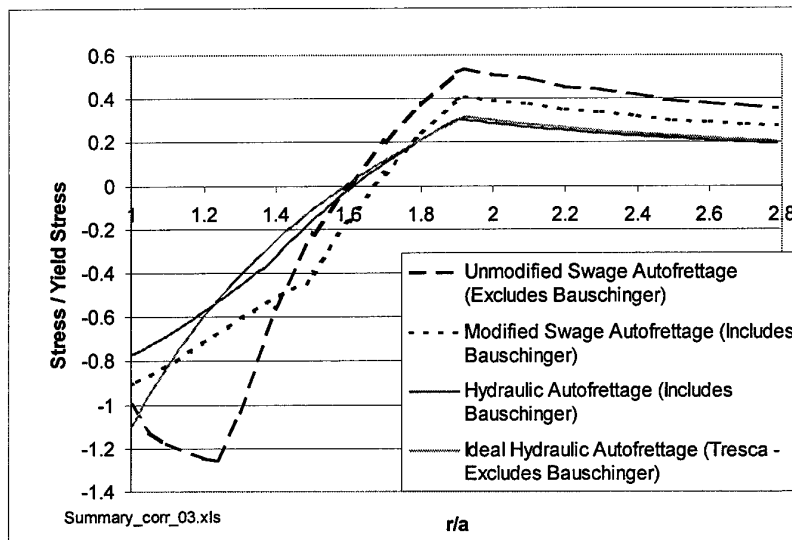
5. Prediction of residual stresses in a swage autofrettaged gun tube and comparison with equivalent stresses in a hydraulically autofrettaged tube

The uniaxial stress profile for current A723 gun steel, obtained as described in (1) above, was used in a novel formulation using program 'HENCKY' to determine the residual stress field for a swage-autofrettaged gun tube. This is believed to be the first solution of this problem.

The results are generally supported by three types of available experimental evidence by comparing 'equivalent' swage and hydraulic autofrettage tubes having the same level of overstrain. Radial slitting of the swaged tube is predicted to show a greater opening angle than its hydraulic equivalent. Fatigue lifetime of the swaged tube is predicted to be significantly higher than the hydraulic case. Re-pressurisation of the equivalent tubes is predicted to produce initial re-yielding at the same pressure in both cases. Analysis of results shows that permanent strains in the swaged tube are expected to appear at a pressure level below that for the hydraulic tube.

Figure 4 summarises the differences between hoop residual stresses in swaged and hydraulically autofrettaged tubes of radius ratio 2.8. An understanding of the differences is important because all current models (including the ASME Pressure Vessel and Piping Code) implicitly assume that, for a given overstrain, the residual stress fields in the two types of tube are identical. This work casts serious doubts upon this assumption.

Reference [5] has been submitted to the ASME Journal of Pressure Vessel Technology and is under review.

Figure 4: Hoop Residual Stresses in Autofrettaged Tube - Comparison of Hydraulic and Swage Autofrettage

6. Preliminary study of possible coating erosion mechanism in a gun tube

During the period of attachment to Benét Laboratory two weeks were devoted to an initial study of the mechanics of a specific, potentially crucial, process involving the loss of coating material from the bore of a gun tube.

The contractor and Mr. J H Underwood of Benét Laboratory have previously identified an important contribution to the loss of coating material, references [6] and [7]. This prior work relates to the static solution for peeling and shear stresses between coating and substrate in a fired gun tube. In the additional work an existing model, due to Hutchinson, was extended to model the fatigue behavior (based upon cyclic range of shear stress) during thermal cycling resulting from firing. This leads to the conclusion that once any loss of coating material occurs, or there is a significant gap in the coating associated with the opening of heat-check cracks, the fatigue stress range is doubled and the rate of interfacial damage is increased by around one order of magnitude. Further development of this model is likely to be the subject of a subsequent research proposal.

7. Preliminary investigation to identify anisotropic behavior in a material which exhibits the Bauschinger effect

The Bauschinger effect is of fundamental importance in calculating the residual stresses that arise during the autofrettage of gun tubes. All previous experimental work has involved a simple uniaxial test (tension followed by compression). The results so obtained are then used as 'equivalent' (usually Von Mises) stress data in numerical packages to determine non-linear material behavior.

Implicit in such an approach is the assumption that the Bauschinger effect manifests itself in an isotropic fashion, i.e. that it is independent of the direction of loading. This assumption has never been tested.

Following discussions, which took place during the contractor's attachment to Benét Laboratory, a simple experimental procedure was devised to test this assumption. Using only two uniaxial tests, undertaken by Mr. E Troiano of Benét Laboratory, it has been demonstrated that the Bauschinger effect exhibits significant anisotropy.

References *(** indicates publications resulting directly from the current contract)*

[1]** Parker, A. P., Troiano, E., Underwood, J. H. and Mossey, C., 2002, "Characterization of Steels Using a Revised Kinematic Hardening Model Incorporating Bauschinger Effect", proceedings of 'Gun Tubes 2002', 15-18 Sep 2002, Oxford, UK. To be submitted to *ASME Journal of Pressure Vessel Technology.*

[2]** Troiano, E., Parker, A. P., Underwood, J. H. and Mossey, C., 2002, "Experimental Data, Numerical Fit and Fatigue Life Calculations Relating to the Bauschinger Effect in High Strength Armament Steels", proceedings of 'Gun Tubes 2002', 15-18 Sep 2002, Oxford, UK. To be submitted to *ASME Journal of Pressure Vessel Technology.*

[3] Parker, A. P., 2001, "Autofrettage of Open End Tubes – Pressures, Stresses, Strains and Code Comparisons", *ASME Journal of Pressure Vessel Technology*, Vol 123, pp. 271-281.

[4]** Underwood, J. H., Moak, D. B., Audino, M. A.. and Parker, A. P., 2002, "Yield Pressure Measurements and Analysis for Autofrettaged Cannons", To be presented at ASME Pressure Vessels and Piping Conference, Vancouver, Canada, August 2002. To be submitted to *ASME Journal of Pressure Vessel Technology.*

[5]** A P Parker, A. P., O'Hara, G. P., and Underwood, J. H., 2002, "Hydraulic Versus Swage Autofrettage and Implications of the Bauschinger Effect", *submitted to ASME Journal of Pressure Vessel Technology.*

[6] Underwood, J. H., Parker, A. P., Cote, P. J., and Sopok, S., 1999, "Compressive Thermal Yielding Leading to Hydrogen Cracking in a Fired Cannon.", *ASME Journal of Pressure Vessel Technology*, Vol 121, 116-120 (1999)

[7] Underwood, J. H. and Parker, A. P., 1999, "Thermal Damage and Shear Failure of Chromium Plated Coating on an A723 Steel Cannon Tube" , presented at ASME Conference on Pressure Vessels & Piping , Boston, August (1999) Published in ASME J Pressure Vessel Tech.

Professor A P Parker

17 January 2002

ANNEX
(a) Unused funds remaining at end of period covered by this report : zero.
(b) No property was acquired with contract funds during the period of this report.

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