DEVELOPMENT OF TYPE II RESIDUAL STRAINS IN INCONEL 690 STEAM GENERATOR MATERIALS

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The development of lattice strains as a function of applied compressive loads was evaluated employing TOF (time of flight) neutron diffraction techniques. Tests were carried out with the compression axis directed at each of the principal directions of an Inconel 690 thick-walled tube specimen. Strain measurements were carried out following sequential in-situ loading and unloading of the specimen with the scattering vector directed both parallel and perpendicular to the compression axis. The strong anisotropic elastic and plastic response observed gave rise to intergranular constraints within the material. This is verified by the crystallographic dependence on the sign and the magnitude of the residual strains measured for several different reflections.

Keywords: Intergranular Strain, Type II Residual Strain, Inconel 690, TOF Neutron Diffraction.

1.0 INTRODUCTION

The predominant failure modes in steam generator tubing are stress related, primarily primary water stress corrosion cracking (PWSCC) and intergranular attack on the secondary side of the tubing followed by a stress corrosion cracking failure (IGASCC) [1]. The rate of occurrence and progression of these defects is highly dependant on the stress state in the material [1].

Current reactors employ Inconel 600 and Incoloy 800 as steam generator tube materials. Previous studies of these alloys have shown that due to the anisotropic mechanical properties of these materials, residual strains and thus stresses can develop on the scale of the grain size of the material [3-8]. These are dependant on the crystallographic orientation of a grain within the polycrystal relative to an applied stress.

This study attempts to characterize the development of these type II residual strains in Inconel 690 which is currently being used in the construction of replacement steam generator vessels for the pressurized water reactors.

2.0 BACKGROUND

2.1 Type II Residual Strain Development

When a polycrystal is loaded, certain families of grains may be oriented in such a way that slip or plastic deformation will take place before the critical resolved shear stress in other systems is reached. As this family of grains undergoes plastic flow, the elastic load they carried as part of the polycrystal is taken up by other orientations not yet reaching their elastic limit. This results in increased elastic strains in these plastically harder orientations. Upon unloading, the permanent deformation which has taken place in the latter grains prevents the harder grains from fully recovering elastically. This results in the formation of an intergranular constraint or type II residual stress within these neighboring grains [2].

The development of these strains is then dependant on the elastic and plastic anisotropy of the material, prior load history as well as the macro and micro texture of the polycrystal being evaluated.

Type II stresses commonly referred to as microstresses are common in polycrystalline materials and equilibrate over many grains. The result is a localized stress field on the scale of grain size [2].

2.3 Previous Work

Previous studies by Holden et al. [3] investigated the residual strain distribution in a sample of bent Incoloy 800 tubing for several different crystallographic directions. Neutron diffraction measurements revealed that both the magnitude and sign of the intergranular constraint was dependant on the reflection measured. The largest of these strains was observed for the (002) reflections. These seemed to be balanced by the (220) and to a lesser extent (111) directions which were opposite in sign. The behavior of each of the lattice reflections in this bent tubing was consistent with subsequent in-situ tensile experiments carried out by Holden et al [4].

Holden et al. [5,6] recorded crystallographic specific residual strains developed in a mildly textured Inconel 600 plate. Neutron diffraction measurements of lattice strains were performed on pre-deformed tension and compression samples strained to +6.0 and -6.0 percent respectively. It was determined that both the magnitude and the sign of the residual lattice strain measured in both the loading and transverse directions were dependant on the reflection measured.

The most significant strains recorded were for that of the (002) and (220) reflections. They were found to be of similar magnitude at approximately 400 microstrain but opposite in sign. The (002) were positive in tension, negative in compression and visa versa for the (220) reflection.

Measurements taken perpendicular to the loading axis in the ND and TD directions of the parent plate material indicate similar magnitudes for the (002) reflections but near zero residual strains for the (220) perpendicular to the loading direction.

EPSC (elasto-plastic self consistent) models have been utilized for predictive purposes for both Inconel 600 and Incoloy 800 with generally favorable results [3-8].

To date, no investigator has evaluated the lattice strain evolution in Inconel 690 materials in a manner similar to the above.

3.0 EXPERIMENTAL

3.1 Materials

Inconel 690 material was provided by Babcock and Wilcox Canada in the form of a thick-walled tube (OD 4 1/4" X ID 2 1/16") from which testing samples were machined. Table 1 shows the chemical content of the alloy. The alloy underwent a mill anneal at 1140 C followed by a final heat treatment at 1320 C for 10.5 hours. Metallographic examination revealed an abundance of annealing twins and a continuous carbide phase at the grain boundaries. Grain size was estimated to be approximately 80 um.

Ni	Cr	Fe	C	Mn	S
59.62	29.65	9.59	0.019	0.29	<0.001
Si	**P**	**Al**	**Co**	**Cu**	**Nb+Ta**
0.28	0.007	0.23	0.008	0.011	0.010

Table 1. Sample Material Chemical Composition

Inconel 690 steam generator tubing samples were employed for texture measurements of the actual in service material. The tubing has an outer diameter of 16 mm and a wall thickness of approximately 1.2 mm.

3.2 Texture Measurements

Samples were taken from the thick-walled tube in the form of 7 mm cubes. Orientations relative to the tube axis (radial, transverse and axial) were indicated and maintained during measurement. In order to obtain bulk texture data, measurements carried out on the steam generator tubing were performed on compound samples composed of 49 1.2 mm wide radial sections. These sections were arranged bound together in a 7 X 7 matrix and aligned in a consistent manner relative to the tube axes.

Texture measurements were carried out on the E3 spectrometer at Chalk River Labs (NRC). The size of the incident and diffracted beams was 50 mm and horizontal collimation of the beam to within 0.4° was achieved with the use of Soller slits. The wavelength chosen for the measurement was 1.471 angstroms. The detector was positioned at scattering angles corresponding to the (111), (200), (311) and (220) diffraction conditions and were made over a complete hemisphere.

3.3 In-Situ Compression Tests

In-situ lattice strain measurements were carried out on the ENGIN-X spectrometer at the ISIS spallation source. Cylindrical test samples 18 mm in length and 9 mm in diameter were cut in axial (A), radial (R) and transverse (T) orientations relative to the axis of the thick-walled tube.

The samples were positioned as below, 45 degrees to the incident beam, providing a 90 degree scattering angle for simultaneous measurement of the strains parallel and perpendicular to the applied compressive load. Incident slit size was fixed at 5 X 4 mm.

The compression samples were oriented in a 100 kN hydraulically actuated Instron load frame. The compressive testing was carried out under load control until yield was observed, at which point the load frame was placed under position control until a target compressive strain of 5% was reached. In some samples this strain was not reached.

Lattice strain measurements were taken at each increasing compressive load. At positions approaching and throughout the plastic regime, the sample was unloaded and lattice strain measurements were taken before proceeding to a higher compressive stress. This allowed for the measurement of any residual lattice strain as a function of bulk compressive strain.

Spectra obtained at each load were fitted with a Gaussian function and compared to a no load spectra. Lattice strain was interpreted in a shift in the position of the peaks for each of the reflections relative to the time of flight or lattice spacing.

4.0 RESULTS

4.1 Sample and I-690 SG Tubing Texture

Pole figures for the (111), (200), (220) and (311) reflections were constructed from neutron diffraction measurements from both the sample and steam generator tubing specimens. These are presented in figures 1 through 3.

Results for the thick-walled tube sample material indicate a relatively mild texture with the (111) planes at 1.4 times random in the axial direction of the tube and 1.2 times random at roughly 30 degrees from the radial axis toward the axial pole. This versus a measured intensity of 4 and 2 times random for the SG tubing respectively.

For the (200) pole figures, intensity is essentially random for the sample material and about 1.5-2 times random at the axial pole for the SG tubing. The (220) orientations are 1.2 versus 2 times random for the sample and SG tubing materials at approx 45 degrees from the radial pole, towards the axial direction.

Measurement of the (311) pole figures indicated random distribution of the poles for both the sample and steam generator tubing materials.

The texture is less pronounced than that measured for the actual steam generator tubing comparison reveals that it is qualitatively similar.

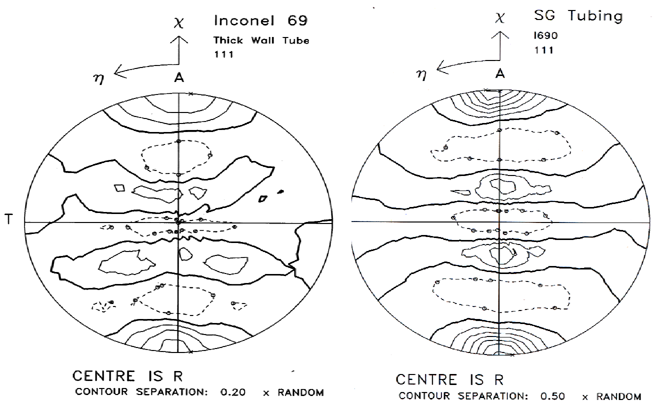

Figure 1. Thick Walled and SG Tubing (111) Pole Figures.

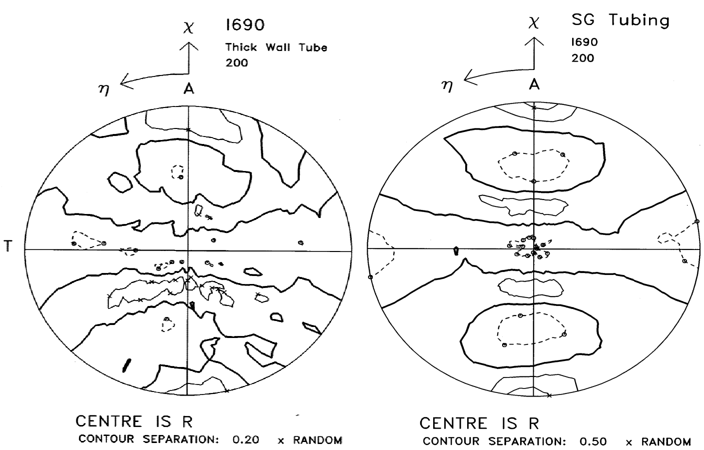

Figure 2. Thick Walled and SG Tubing (200) Pole Figures

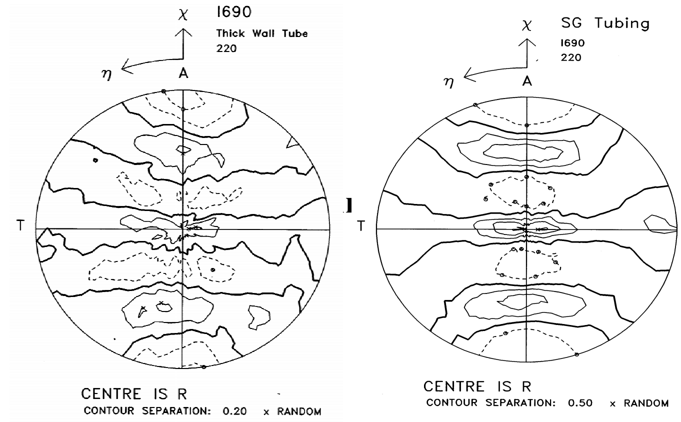

Figure 3. Thick Walled and SG Tubing (220) Pole Figures.

4.2 In-situ Compression Testing

Figures 4 through 9 display the results of the lattice strain measurements for the in-situ compression testing. Shown are both the at load and the residual strains at 5 MPa, taken as the zero reference. The residuals are plotted as a function of the at load true stress prior to unloading the sample for measurement.

For the at load data in all orientations (A,R,T), clear anisotropic elastic behavior is observed both parallel and perpendicular to the applied loads. Elastic compliance decreases for the (002), (311), (220) and (111) orientations respectively.

The (200) grains oriented parallel to the direction of applied load appear to yield at approximately 200 MPa. For this orientation, the curve veers to the left relative to the elastic regime. This is contrasted by the (220) and (111) grains which veer to the right of the initial elastic response. The deviation from linearity is much more pronounced for the (111) and (220) reflections. As the (200) grains undergo plastic flow, any load exceeding their critical resolved shear stress is transferred to the (111) and (220) orientations within the polycrystal. Strain measurements taken perpendicular to the applied load show a similar behavior for the respective orientations.

The residual strains which develop are a strong function of the applied plastic load and appear in conjunction with the yield behavior noted in the at load strains. The most significant of these is seen for the (002) orientations reaching a maximum of -300 με. These residual strains are balanced by the (111) and (220) orientations which display smaller residual elastic constraints at a maximum of 100 and 200 με respectively. Similar behavior is observed for measurements perpendicular to the loading directions, however with slightly decreased magnitudes in all cases.

A noted difference in the nature of the balance provided by the (111) and (220) orientations is observed relative to the applied load and the measurement direction. For measurements with the scattering vector (Q) parallel to the load, the magnitude of the (111) and (220) residual strains appears to be nearly equal in magnitude. Residual strains measured with Q perpendicular to the applied load show a more pronounced development for the (220) orientations.

Tests were performed in each of the principal directions of the sample tubing. In a qualitative sense, the behavior of the material is similar for samples loaded in each of the principal directions both for data gathered with Q parallel and perpendicular to the applied load. This is not unexpected but verified by the weak initial texture of the sample materials. The data shown graphically are for samples loaded in the axial direction of the parent tube material.

5.0 CONCLUSIONS

Significant anisotropic elastic and plastic behavior are observed during in-situ compression testing of Inconel 690. This anisotropy gives rise to intergranular constraints which result in the development of significant type II residual strain following compressive loading. The magnitude and the sign of these residual strains were found to be dependant on the crystallographic orientation of grains within the polycrystal.

The most significant strains were observed for the (002) orientations with Q parallel and perpendicular to the direction of load. These strains were balanced by the (220) and (111) crystals to varying extents. Behavior in terms of the magnitude and sign of the residual strain development is consistent with studies noted for Inconel 600 and Incoloy 800 testing.

The development of these type II residual strains requires consideration for the longevity of steam generator tubing components. In order to accurately predict the residual stress field present in a component, these type II stress fields must be considered in addition to any type I or macrostress fields assumed for the manufactured components. The predominant failure modes for steam generator tubing materials are stress related [1]. The addition of this type II component is relevant, as it will affect both the rates of occurrence and progression for failure modes such as stress corrosion cracking.

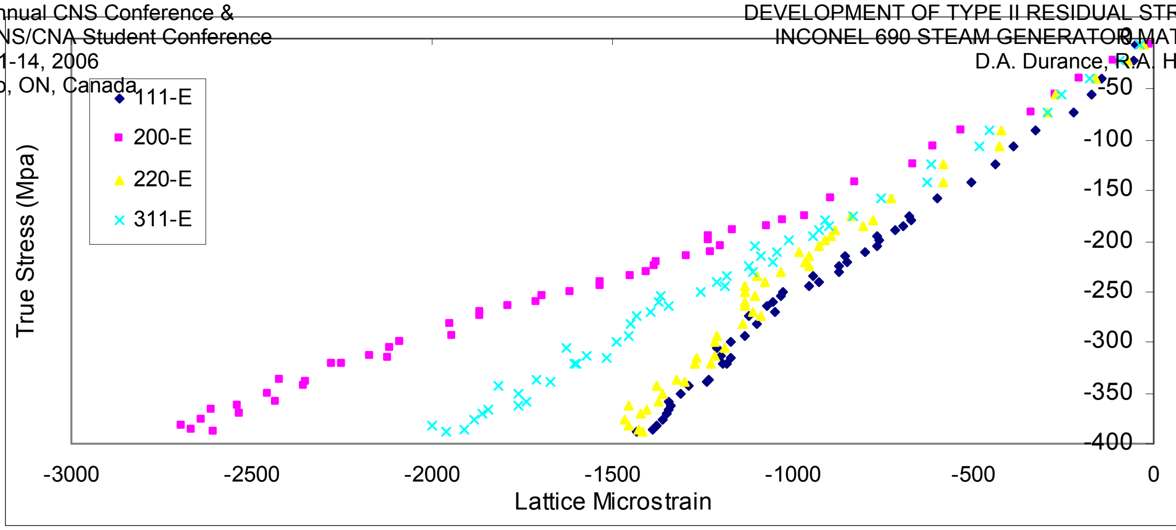

Figure 4. Sample CA3 At Load Strains (Axial Compression/Axial Scattering Vector (Q))

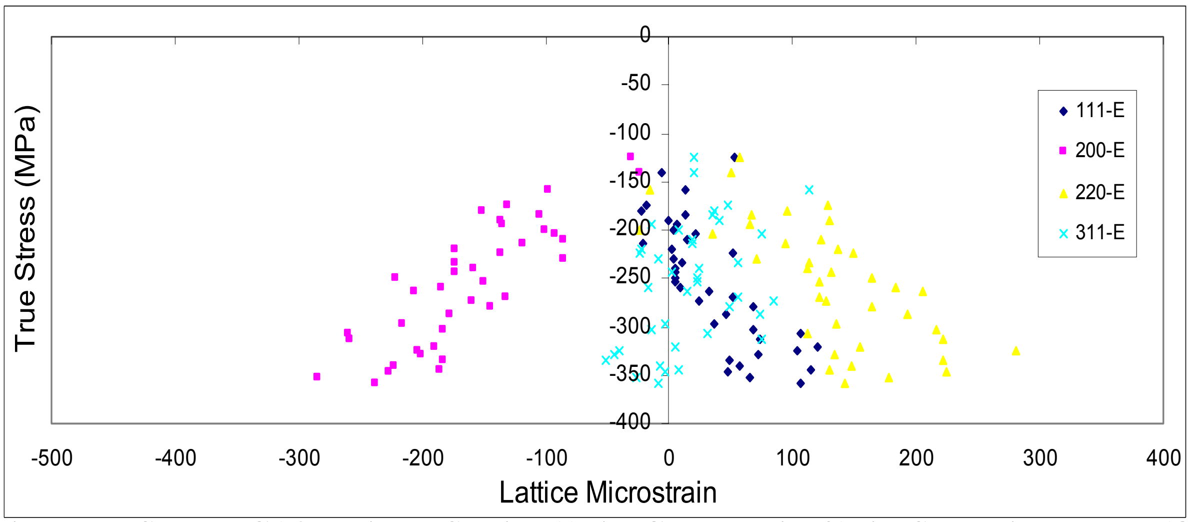

Figure 5. Sample CA3 Residual Strains (Axial Compression/Axial Scattering Vector (Q))

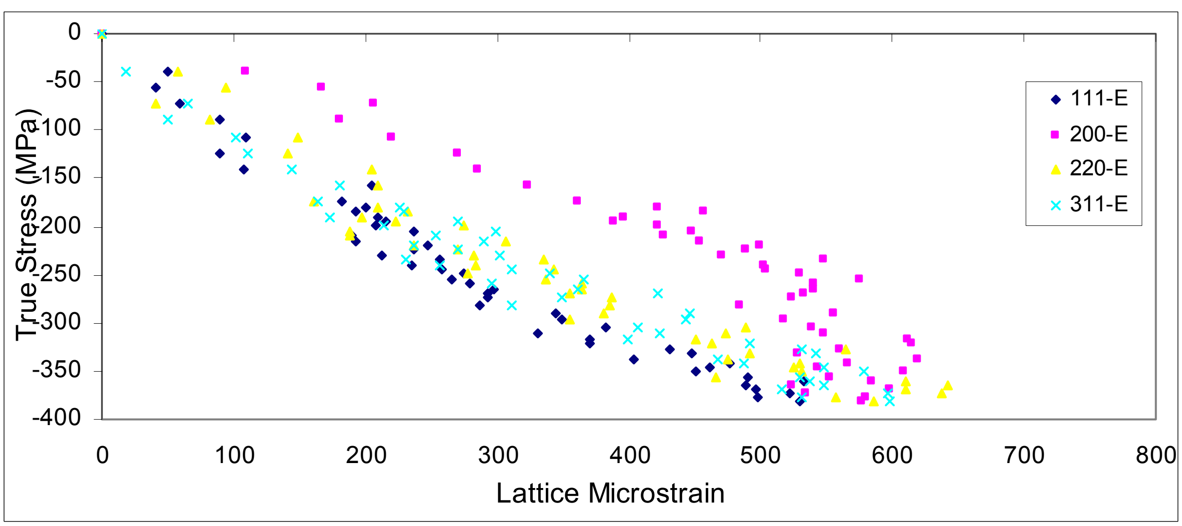

Figure 6. Sample CA1 At Load Strains (Axial Compression/Trans Scattering Vector (Q))

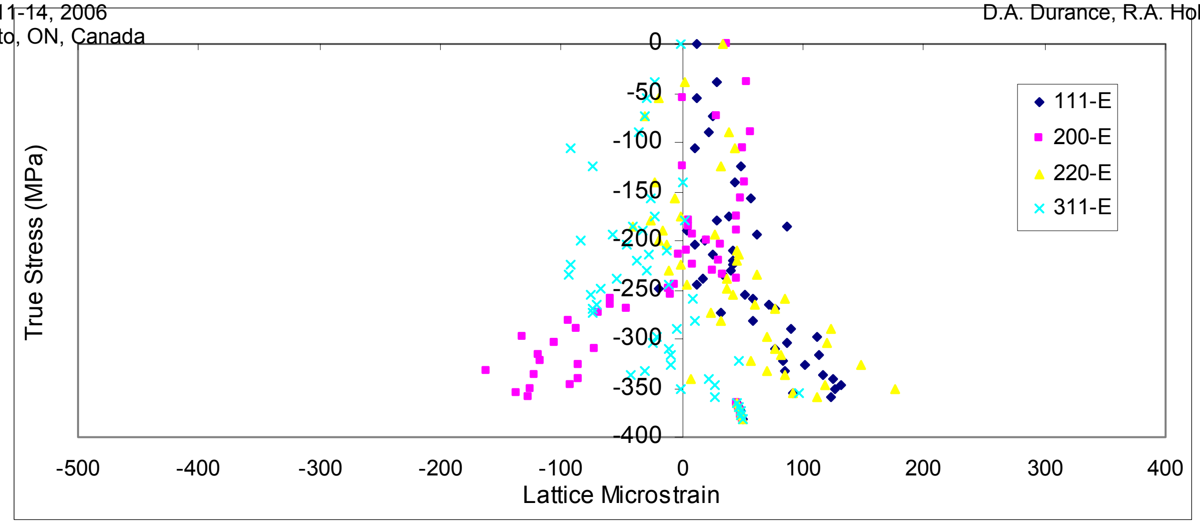

Figure 7. Sample CA1 Residual Strains (Axial Compression/Trans Scattering Vector (Q))

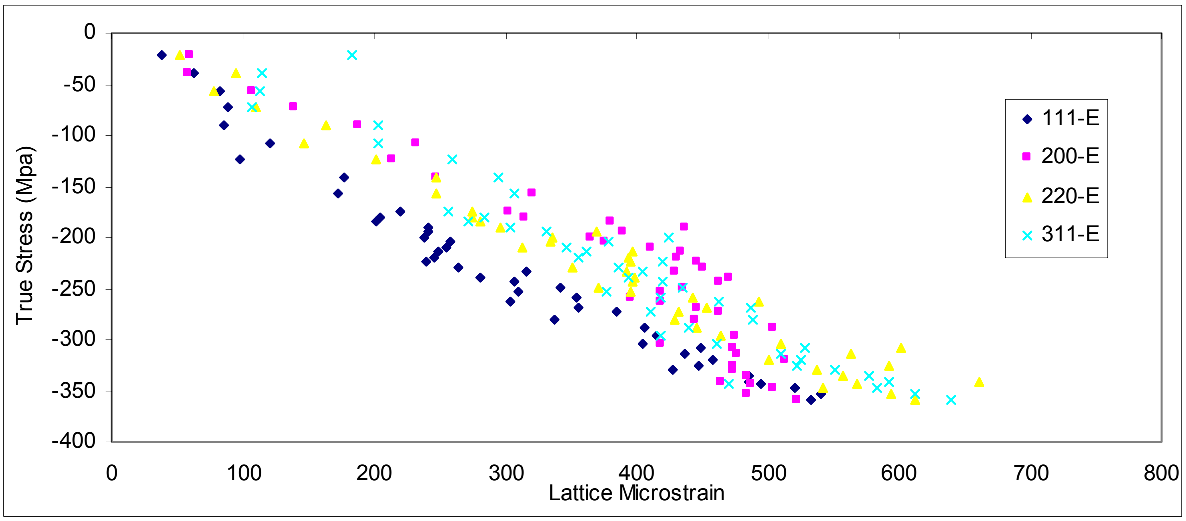

Figure 8. Sample CA3 At Load Strains (Axial Compression/Radial Scattering Vector (Q))

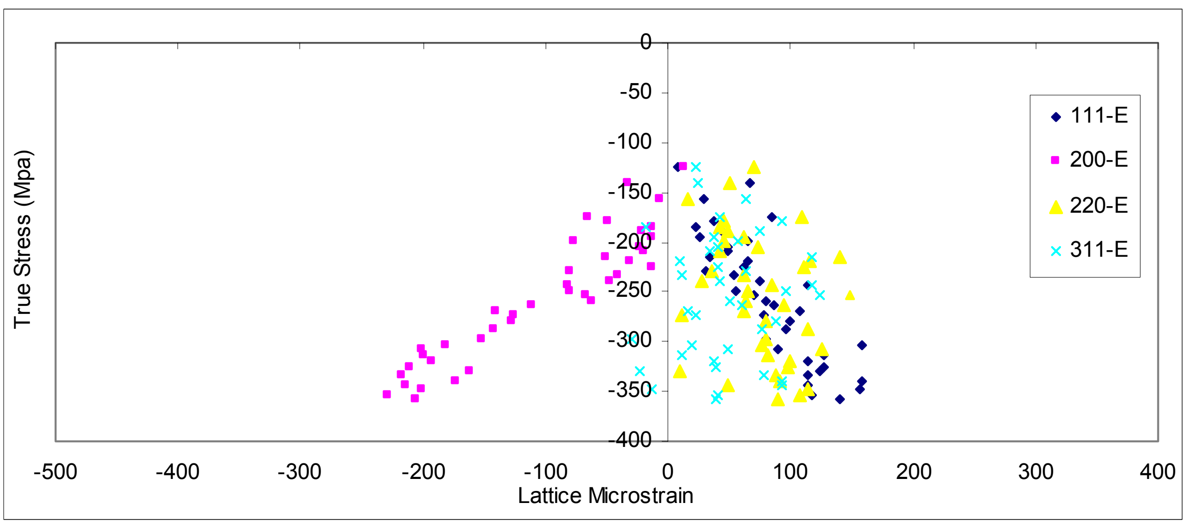

Figure 9. Sample CA3 Residual Strains (Axial Compression/Radial Scattering Vector (Q))

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