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Fracture Toughness, Thermo-Electric Power, and Atom Probe Investigations of JRQ Steel in I, IA, IAR, and IARA Conditions

ABSTRACT: The International Atomic Energy Agency has sponsored a number of studies involving a specific plate of A533 grade B class 1 steel designated heat JRQ. In this cooperative study between the Paul Scherrer Institute (PSI) and the Heavy-Section Steel Irradiation Program of Oak Ridge National Laboratory (ORNL), groups of Charpy impact, tensile, and precracked Charpy specimens of the JRQ plate were irradiated by PSI to four different fast neutron fluences [from 0.39 to 5.0 \times 10^{23} \text{ n/m}^2 (>1 \text{ MeV})] in a test reactor. Additional specimens were given a post-irradiation thermal annealing treatment at 460°C for 18 h when 50 % of the target fluence was reached, followed by reirradiation to the same target fluences for the four groups of irradiated specimens. Additionally, ORNL thermally annealed some of the reirradiated specimens, as well as some of those in the irradiated only condition. Charpy impact, tensile, fracture toughness, and hardness tests have been performed to evaluate material response in the various conditions and to compare with the unirradiated material. Additionally, thermo-electric power experiments have been conducted by PSI, while atom probe tomography evaluations have been conducted by ORNL. Except at the highest fluence, the results show that the material given an intermediate annealing treatment exhibited irradiation-induced transition temperature shifts about the same as those that were only irradiated. However, the upper-shelf energies were generally higher and the yield strengths were generally lower for the reirradiated groups. The intermediate thermal annealing resulted in less reirradiation embrittlement of fracture toughness than Charpy impact toughness, while annealing after reirradiation resulted in significant increases in Charpy upper-shelf energy above that in the unirradiated condition. Irradiation-induced and IAR Charpy impact transition temperature shifts exhibit a nearly linear correlation with Seebeck coefficient in the I and IAR conditions. ORNL has also sent additional specimens from I, IA, IAR, and IARA test of JRQ for additional TEP testing. After irradiation, a high number density of ultrafine Cu-, Mn-, Ni-, Si-, and P-enriched precipitates were observed by atom probe tomography. Phosphorus segregation to dislocations was also observed. A significantly lower number density of larger Cu-, Mn-, and Ni-enriched precipitates was observed after the second annealing treatment.

KEYWORDS: Charpy impact, fracture toughness, irradiation, precracked Charpy, reactor pressure vessel, reirradiation, tensile strength, thermal annealing

Introduction

One of the critical issues associated with license extension of commercial nuclear power plants is irradiation-induced embrittlement of the reactor pressure vessel (RPV). Embrittlement of the RPV beltline material may result in sufficient restriction of the pressure-temperature operating conditions such that mitigation of the embrittlement through thermal annealing is necessary. If thermal annealing of the RPV is considered as a means to recover the fracture
toughness of an embrittled RPV, then the post-annealing reirradiation response of the steel must be evaluated. In the United States, for example, *Title 10, U.S. Code of Federal Regulations, Part 50* [1] specifies thermal annealing of the RPV as one method for recovering the fracture toughness and refers to *Regulatory Guide 1.162 (RG 1.162)* [2]. That regulatory guide provides guidelines for determining the percent recovery and the re-embrittlement trend and for establishing the post-anneal reference temperature and Charpy upper-shelf energy values. The re-embrittlement trend in RG 1.162 is based on the “lateral” shift procedure in which re-embrittlement of the steel is assumed to occur at the same rate as in the irradiated case. The amount of post-annealing reirradiation data for pressurized water reactors is sparse, especially regarding fracture toughness data. A plate of A533 grade B class 1 steel designated heat JRQ has been used for many research studies around the world, particularly those sponsored by the International Atomic Energy Agency (IAEA). As part of the IAEA coordinated research program (CRP) on “Optimizing of Reactor Pressure Vessel Surveillance Programmes and Their Analyses,” designated CRP 3, the Paul Scherrer Institute (PSI) conducted irradiation, annealing, and reirradiation studies with the JRQ steel. Some of the reirradiated specimens were not tested at the time of the CRP but were stored at PSI for future testing. The Heavy-Section Steel Irradiation (HSSI) Program at Oak Ridge National Laboratory (ORNL) and PSI are collaborating on a program that includes testing of the remaining specimens stored at PSI, annealing and further reirradiation of selected specimens, and microstructural examination of the material in all conditions. The results of mechanical property and fracture toughness tests have been reported previously [3,4]. This paper provides a summary of those test results and presents the results from thermo-electric power (TEP) and atom probe tomography (APT) experiments with specimens in the various conditions of irradiation and annealing.

**Material**

The JRQ steel is a medium-copper (0.14 wt%) A533 grade B class 1 plate of 225-mm thickness. Relative to predicted radiation sensitivity [by *U.S. Regulatory Guide 1.99, Revision 2 (RG 1.99-2)*] [5], it is very similar to that of another well-known reference steel, Heavy-Section Steel Technology (HSST) Plate 02, with chemistry factors of 58 and 57°C, respectively. Table 1 provides the chemical compositions of those two steels.

<table>
<thead>
<tr>
<th>Material</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
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<tr>
<td>JRQ</td>
<td>0.18</td>
<td>0.24</td>
<td>1.42</td>
<td>0.017</td>
<td>0.004</td>
<td>0.14</td>
<td>0.84</td>
<td>0.12</td>
<td>0.51</td>
<td>0.002</td>
</tr>
<tr>
<td>Plate 02</td>
<td>0.23</td>
<td>0.20</td>
<td>1.55</td>
<td>0.009</td>
<td>0.014</td>
<td>0.14</td>
<td>0.67</td>
<td>0.04</td>
<td>0.53</td>
<td>0.003</td>
</tr>
</tbody>
</table>

The JRQ plate has average room temperature yield and ultimate strengths of 470 and 650 MPa, respectively, while those for Plate 02 (305-mm thick) are 467 and 622 MPa, respectively. Testing of JRQ by PSI resulted in a 41-J temperature of −28°C and an upper-shelf energy of 200 J, compared with 5°C and 140 J, respectively, for HSST Plate 02. Thus, the tensile strengths for the two plates are similar, but the JRQ plate exhibits superior Charpy impact toughness, one factor for which could be the greater thickness (~305 mm) of Plate 02.

Charpy V-notch (CVN) impact and precracked Charpy (PCVN) fracture toughness specimens were machined out of the JRQ block at the ¼ thickness layer and with notches
machined for the T-L orientation. Tensile specimens were machined from Charpy-size blanks with their axes parallel to the direction of forging and also from the ¼ thickness layer.

Experimental Procedures

Irradiations by PSI were performed in the 10 MW (t) SAPHIR reactor at 290°C and at a neutron flux of ~5 × 10^{16} n/m² (>1 MeV) to four fluences from 0.39 to 5 × 10^{23} n/m² (>1 MeV). Additional specimens were thermally annealed at 460°C for 18 h when 50% of the target fluence was reached, followed by reirradiation (IAR) to the same four target total fluences. Tensile and Charpy impact test procedures used at PSI and ORNL were described in [4]. Fatigue precracking of all PCVN specimens was performed by PSI. Fracture toughness testing at ORNL was performed under machine displacement control in a servohydraulic machine in the hot cell. The system is computer controlled using in-house developed software and hardware similar to that described in [6]. Thermal annealing of irradiated and reirradiated specimens at ORNL was performed in an air circulating oven in the hot cell with temperature measured by a thermocouple buried in the group of specimens.

Summary of Mechanical Property and Fracture Toughness Results

As stated earlier, the mechanical property and fracture toughness test results were presented and discussed previously [3,4]. Those results are summarized here for clarity and to provide a perspective for the TEP and APT results. The intermediate thermal annealing schedule of 460°C for 18 h was selected by PSI based on a relatively large program of experimental studies [3] and is also discussed in [4]. The results indicated that annealing at 460°C for 18 h would result in microhardness recovery of 90% or more. This result is in good agreement with the prediction of U.S. NRC Regulatory Guide 1.162, which predicts transition temperature recoveries of 89% and 94% for JRQ annealed at 460°C/18 h and 460°C/168 h, respectively.

Tensile tests were conducted at room temperature by PSI and, as expected, the intermediate anneal had a mitigating effect on the irradiation-induced hardening at a given total fluence [3,4]. On average, the specimens given the intermediate thermal anneal exhibited about half the yield and ultimate strength increases of those that were not annealed. No tests were performed for material in the irradiated/annealed condition, so the actual hardening recovery due to annealing is not known.

Charpy impact tests were conducted in both the irradiated and the IAR conditions to four different total fluences. Figure 1 shows the results of absorbed energy versus test temperature with the actual data shown only for the unirradiated condition. All the curve fits were performed using the hyperbolic tangent function with the lower shelf fixed at 2.7 J. In both cases, increasing fluence results in shifts of the transition temperatures to higher temperatures as expected. As stated earlier, additional annealing experiments were performed by ORNL. Charpy impact specimens in the IAR (0.5) condition (this means irradiated to 0.25 × 10^{23} n/m², annealed at 460°C for 18 h, then reirradiated to 0.25 × 10^{23} n/m² for a total fluence of 0.5 × 10^{23} n/m²) were given an additional anneal (IARA) at 460°C for 18 h. Similarly, Charpy impact specimens in the IAR (1.7) condition (meaning 0.85 × 10^{23} n/m² for the irradiation step and for the reirradiation step) were reannealed (IARA) at 460°C/168 h. Figure 2 shows graphically the data and the curve fits obtained and compared with the material in the unirradiated and IAR curve fits obtained and compared with the material in the unirradiated and IAR conditions. As shown, the annealing
treatments following reirradiation provide essentially full recovery of the CVN transition temperature as well as recovery of upper-shelf energy to levels above those of the unirradiated material.

FIG. 1—Charpy impact results comparing (a) irradiated and (b) IAR conditions at four fluences with the unirradiated material.
FIG. 2—Charpy impact energy versus temperature for JRQ steel following thermal re-annealing (IARA) of material in the (a) IAR (1.7) and (b) IAR (0.5) conditions compared with the IAR and unirradiated conditions.
The influences of these various annealing treatments on reembrittlement and on recovery, however, are not clear by examination of the curves in Figs. 1 and 2. In Fig. 3 the results are compared with the embrittlement predictions of RG 1.99-2. The correlation of Eason, Wright, and Odette [7] results in predicted shifts within 1.5°C for all four fluences. Of course, the predictions are only applicable to the initial irradiation. Figure 3a shows that the intermediate anneal at 460°C/18 h had no mitigating effect on the 41-J shifts except at the highest fluence, but Fig. 3b shows that the intermediate anneal treatment did have an effect on the Charpy upper shelf energy, in that the upper shelf energies are higher for all the IAR conditions compared with the irradiated condition. The figures also show nearly full or greater than full recovery of the 41-J temperatures and recoveries of upper-shelf energy well above that of the unirradiated condition in the re-annealed (IARA) condition. The annealing-induced increase in upper-shelf energy for the material in the IAR (0.5) condition is particularly significant, resulting in an upper-shelf energy of about 90 J above that of the unirradiated material.

As discussed in [4], the RG 1.99-2 fluence function was fit to the irradiated data to determine an effective chemistry factor. The resultant effective chemistry factor in this case is 44°C compared with the value of 58°C based on the RG 1.99-2 tables. As discussed, the data clearly show that the IAR data are essentially the same as those for the material in the irradiated only condition. In the case of the IARA data, the results show relatively good agreement with the predictions of RG 1.162 for annealing recovery.

A comparison of the CVN transition temperature shifts with yield strength increases for the material in the various irradiated only conditions and the IAR conditions revealed substantial disparities that are presented and discussed in [4]. The results showed that the four irradiated cases are in reasonable agreement with the observations in the literature [8,9], but there are some disparities for at least two of the IAR cases.

As mentioned earlier, all the PCVN specimens were fatigue precracked and irradiated by PSI, while fracture toughness testing was performed by ORNL. The only irradiated specimens available were those irradiated to $5 \times 10^{23}$ n/m$^2$. Thus, some of those specimens were tested in the irradiated condition, while others were annealed at 460°C/168 h (IA) and tested to evaluate recovery of fracture toughness. Additionally, PCVN specimens were available in the IAR (0.5) and IAR (1.7) conditions and also tested by ORNL. The fracture toughness results were presented and discussed in detail in [4], including a discussion regarding crack length/widths of 0.3 and 0.5. Figure 4 shows the results of those tests in terms of fracture toughness adjusted to 1T specimen size versus test temperature. Unirradiated fracture toughness data were not obtained by PSI for this program; however, recent data from an IAEA CRP, entitled “Assuring Structural Integrity of Reactor Pressure Vessels,” provides an overall $T_o$ of $-71$°C for a large number of PCVN specimens tested by 22 institutes in 18 countries [10]. This value of $T_o$ is assumed as the value for JRQ in the unirradiated condition in this paper. Thus, the recovery of fracture toughness due to annealing is estimated to be 123%.

Figure 5 graphically provides the results of PCVN testing for the IAR (0.5) and the IAR (1.7) conditions. The $T_o$ values are $-94.7$°C and $-37.3$°C for the IAR (0.5) and IAR (1.7) conditions, respectively. Thus, for reirradiation to $0.5 \times 10^{23}$ n/m$^2$ with an intermediate anneal at 460°C/18 h the intermediate anneal appears to have had a mitigating effect on reirradiation embrittlement in that the $T_o$ temperature is below the estimated value for the unirradiated condition and about the same as that for the IA condition shown in Fig. 4. For the IAR (1.7) condition, the $T_o$ temperature is about 34°C higher than that for the assumed unirradiated condition and about
57°C higher than that of the IA condition shown in Fig. 4. By comparison, the CVN 41-J transition temperature of the IAR (1.7) material is 56°C higher than the unirradiated condition.

**FIG. 3**—Graphical summary of the changes in (a) Charpy 41-J transition temperature shift and (b) Charpy upper shelf energy of JRQ steel in the irradiated IA, IAR, and IARA conditions.
FIG. 4—Fracture toughness (adjusted to 1T specimen size) of JRQ steel in irradiated and irradiated/annealed conditions as determined with PCVN specimens.

FIG. 5—Fracture toughness (adjusted to 1T specimen size) versus temperature for JRQ steel following two IAR conditions as determined with PCVN specimens.
Results of Thermo-Electric Power Experiments

The TEP experiments were conducted by PSI to investigate a potential correlation between the Seebeck Coefficient and irradiation embrittlement. This paper summarizes the results of the experiments, while a more detailed description of the procedures and background of the TEP method are discussed by Niffenegger, Reichlin, and Kalkhof [11]. In essence, the Seebeck effect arises from a small electric current that accompanies heat flow in a material. The thermo-electric potential (TEP) generated is proportional to the temperature gradient with the proportionality factor defined as the Seebeck Coefficient. The basic concept is that the TEP response of the material will change with the irradiation-induced changes in the microstructure. To perform the measurements, PSI used the TEP device developed by the Institute National des Sciences Appliquées de Lion (INSA). The device consists of two parts, one to apply a temperature gradient on the test specimen (Charpy type specimens for this study) and to measure both the temperatures and the TEP, with the second part being data acquisition and control instrumentation. The specimen is placed onto two copper supports and held in place with a pneumatic piston at a constant pressure so that two contact lines are maintained, one at 15°C and the other at 25°C with an accuracy of ±0.1°C in these experiments [11]. The sensitivity of the TEM measurement is 0.002 µV/°C, with an expected error of 0.2% of the measured value. It is noted that TEP measurements are sensitive to the specimen surface condition and to material inhomogeneities; thus, PSI mechanically polished the Charpy specimens to minimize the surface effect. Figure 6 shows the Seebeck Coefficient versus fluence for the JRQ specimens in the irradiated condition. Measurements were made both with the V-notch in the up position and the behind positions (180° difference). A number of measurements at each fluence was made with the curve fit to the data shown in the figure.

[Graph showing the Seebeck Coefficient of Irradiated JRQ-Specimens]
In Fig. 7, a similar plot is shown with results of measurements on specimens in the IAR condition, while all the results are plotted together in Fig. 8. The same curve fit as shown in Fig. 6 shows that the IAR condition gives the same correlation between TEP and irradiation-induced embrittlement. This is particularly evident with the IAR results at the highest fluence in that the transition temperature shifts shown in Fig. 2 and the TEP results shown in Figs. 7 and 8 both indicate somewhat of a decrease in the trend from the lower fluence results. In Fig. 9, the Charpy 41-J and 68-J shifts are plotted versus the Seebeck Coefficient for the irradiated specimens and exhibit a nearly linear correlation.

Thus, these results indicate that TEP may be a useful technique for monitoring the irradiation-induced embrittlement of RPV steels. However, as pointed out in [11], the method is extremely sensitive to surface condition and material inhomogeneities. Thus, the authors of [11] suggest the development of a thermoelectric scanning microscope that would utilize a different method of heat load (e.g., LASER) to avoid surface sensitivities and may offer the potential to produce a 3-dimensional plot that would allow for visualization of localized damage and the distribution of inhomogeneities.

A further investigation with TEP is reported by Odette, Cowan, and Gragg [12], in which changes in the Seebeck coefficient are combined with changes in electrical resistivity to characterize solute redistribution during irradiation and aging. The authors examined a large number of materials under different irradiation and thermal aging conditions. They compared their results with irradiation-induced yield strength changes and observed reasonable correlations, including good agreement with results of other techniques such as small-angle neutron scattering [12].

![Graph showing Seebeck coefficient versus neutron fluence for JRQ steel in IAR conditions.](image-url)
FIG. 8—Seebeck coefficient versus neutron fluence for JRQ steel in the I and IAR conditions.

FIG. 9—Irradiation-induced Charpy 41-J and 68-J transition temperature shifts versus Seebeck coefficient.
Thus, based on earlier work in this area as well as the studies in [11] and [12], it appears that the TEP technique to determine the Seebeck coefficient offers another potential tool to estimate embrittlement using noninvasive means, especially if a baseline set of measurements is available with the material of interest. When combined with electrical resistivity, an even more powerful tool appears to hold promise for a noninvasive means to discriminate the elemental contributions to embrittlement.

Results of Atom Probe Tomography Experiments

Atom probe tomography (APT) of the JRQ steel was performed to reveal the evolution of microstructural features following various stages of irradiation, annealing, and reirradiation. Because of the extremely small size of the features responsible for embrittlement in RPV steels, it has been demonstrated that the APT technique can provide an effective means to characterize those microstructural features [13]. Atom probe field ion microscopy and APT have firmly established that a high number density of ultra-fine copper-, manganese-, nickel-, and silicon-enriched precipitates are produced in copper-containing pressure vessel steels by neutron irradiation. These precipitates are a primary cause of the degradation in the mechanical properties of these materials during service in a nuclear reactor. Moreover, as is well known, the mechanical properties of RPV steels may be recovered by thermal annealing the RPV at a temperature of ~450ºC for about one week. In this APT study, the number density, size, and composition of these ultrafine precipitates have been studied through the two irradiation and annealing cycles, meaning in the I, IA, IAR, and IARA conditions. The Oak Ridge National Laboratory local electrode atom probe LEAP® was used for the experiments discussed here [14], while further background information regarding this new type of atom probe system can be found in [15,16]. With the LEAP®, the size and close proximity of the local electrode to the specimen reduces the voltage that is required to field evaporate ions from the specimen by 35–65 % compared to the 3-dimensional atom probe. Therefore, lower amplitude pulse voltages are required and can be generated at faster repetition rates, resulting in the ability to obtain significantly more ions per second. Figure 10 shows a series of atom maps for elemental copper, manganese, nickel, silicon, and phosphorus in the JRQ steel following irradiation to $5 \times 10^{23} \text{n/m}^2 (>1 \text{MeV})$. In this condition, a high number density of ultrafine Cu-, Mn-, Ni-, Si-, and P-enriched precipitates were observed. By visual inspection of the atom maps, the coincidence of those elements in the various precipitates (darker spots on the atom maps) can be seen. Additionally, phosphorus segregation to dislocations was also observed in this case.

As mentioned earlier, some of the precracked Charpy specimens irradiated to $5 \times 10^{23} \text{n/m}^2 (>1 \text{MeV})$ were subsequently annealed at 460ºC for 18 h by ORNL. The fracture toughness results were shown in Fig. 4, while atom probe tomography examination results are shown in Fig. 11. Contrary to the results in Fig. 10, copper-enriched precipitates were only observed near grain boundaries. Moreover, the number density of the precipitates was about one order of magnitude less, and they were substantially larger than in the irradiated only case. Additionally, phosphorus segregation was observed on grain boundaries.

Figure 12 shows atom maps of JRQ steel following irradiation, annealing, and reirradiation in the $I_{0.85}AR_{0.85}$ condition, in which case the intermediate anneal was conducted at 460ºC for 18 h. Following annealing and reirradiation to a total fluence of $1.7 \times 10^{23} \text{n/m}^2 (>1 \text{MeV})$, atom probe tomography revealed some copper-enriched precipitates of smaller size than in the specimens irradiated only to $5 \times 10^{23} \text{n/m}^2$. The number density is similar to that for the specimens irradiated to the higher fluence, but with a somewhat smaller radius. As with the
higher fluence condition, phosphorus segregation to dislocations was also observed in the IAR case.

FIG. 10—Atom maps of JRQ steel following irradiation to $5 \times 10^{23} \text{n/m}^2 (>1 \text{MeV})$.

FIG. 11—Atom maps of JRQ steel following irradiation to $5 \times 10^{23} \text{n/m}^2 (>1 \text{MeV})$ and thermal annealing at 460°C for 18 h.
FIG. 12—Atom maps of JRQ steel following irradiation to $0.85 \times 10^{23} \text{n/m}^2 (>1 \text{MeV})$, thermal annealing at 460°C for 18 h and reirradiation to $0.85 \times 10^{23} \text{n/m}^2$ for a total fluence of $1.7 \times 10^{23} \text{n/m}^2$.

Some of the I$_{0.85}$AR$_{0.85}$ specimens were reannealed at 460°C for 168 h to examine the effect of a longer time thermal anneal treatment on the reirradiated material. The effects on Charpy impact toughness were discussed earlier and presented in Figs. 2 and 3, which showed almost full recovery of the 41-J transition temperature and an increase in upper-shelf energy substantially above that for the unirradiated condition. Atom probe tomography revealed a substantially lower number density of larger Cu-, Mn-, and Ni-enriched precipitates following this second annealing treatment, as seen in Fig. 13. As with the first annealing treatment (I$_{0.85}$A), the precipitates were larger than in the I or IAR conditions. As with all the other conditions examined, phosphorus segregation at dislocations was also observed in this case.

FIG. 13—Atom maps of JRQ steel following irradiation to $0.85 \times 10^{23} \text{n/m}^2 (>1 \text{MeV})$, thermal annealing at 460°C for 18 h, reirradiation to $0.85 \times 10^{23} \text{n/m}^2$ (for a total fluence of $1.7 \times 10^{23} \text{n/m}^2$), and reannealing at 460°C for 168 h.
Conclusions

Irradiations of A533 grade B class 1 plate steel (heat JRQ) were conducted at 290°C to four target fluences from 0.39 to 5 × 10^{23} \text{n/m}^2 (\geq 1 \text{ MeV}), with additional specimens annealed at 460°C for 18 h when 50% of the target fluence was reached, followed by reirradiation to the target fluence. Charpy impact, tensile, and PCVN quasi-static fracture toughness tests have been performed in various irradiated (I), IA, IAR, and IARA conditions. Thermo-electric power experiments were performed with specimens in the I and IAR conditions to measure the Seebeck coefficient, and atom probe tomography experiments were conducted to reveal the evolution of microstructural features following the various stages of irradiation, annealing, and reirradiation. Based on the experiments conducted, the following observations and conclusions are made:

1. Except at the highest fluence (5 × 10^{19}), the intermediate annealed specimens exhibited about the same Charpy 41-J shifts as those only irradiated, although the upper-shelf energy decreases were less for the intermediate annealed specimens.
2. Thermal annealing resulted in less reirradiation embrittlement of fracture toughness than Charpy impact toughness.
3. Irradiation-induced and IAR Charpy impact transition temperature shifts exhibit a nearly linear correlation with Seebeck coefficient. ORNL has sent specimens from I, IA, IAR, and IARA tests of JRQ for TEP testing.
4. After irradiation, a high number density of ultrafine Cu-, Mn-, Ni-, Si-, and P-enriched precipitates were observed. Phosphorus segregation to dislocations was also observed. A significantly lower number density of larger Cu-, Mn-, and Ni-enriched precipitates was observed after the second annealing treatment.
5. The TEP technique to determine the Seebeck coefficient offers another potential tool to determine embrittlement using noninvasive means. When combined with electrical resistivity, an even more powerful tool appears to hold promise for a noninvasive means to discriminate the elemental contributions to embrittlement.

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