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**Thermoelectric NDE for Characterization of Fracture Properties of Mechanically Embrittled Austenitic Stainless Steel**

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**Summary**

Thirty-two specimens provided by EPRI were tested by thermoelectric and magnetic nondestructive characterization techniques in this study. These specimens were made of four types of austenitic stainless steel plate material (SS-304, SS-316, SS-347, and SS-A286) that were first cold-rolled in a range of 0%-80% thickness reduction to simulate increasing dislocation density associated with fast neutron irradiation embrittlement and were subsequently machined into 0.5”-thick compact tension (CT) specimens. These specimens were characterized by two thermoelectric Nondestructive Evaluation (NDE) techniques, namely a commercially available two-point thermoelectric alloy sorter and a high-precision automated four-point thermoelectric power (TEP) measurement system developed at the University of Cincinnati (UC). The first technique allowed highly localized “hot-spot” measurements with good spatial resolution even on these relatively small CT specimens, while the second technique offered higher repeatability and absolute accuracy. Both types of thermoelectric measurement indicated the same basic patterns of changing TEP with cold work. The two austenitic stainless steel alloys that were known to undergo significant martensitic phase transformation during low-temperature plastic deformation, namely SS-304 and SS-347, exhibited strong increase in TEP with increasing cold work, while the other two alloys that experience very modest or no martensitic phase transformation due to plastic deformation, namely SS-316 and SS-A286, exhibited relatively weak decrease in TEP with increasing cold work. Since it is well known that martensitic phase transformation causes a significant increase of magnetic susceptibility in otherwise weakly paramagnetic austenitic stainless steels, magnetic susceptibility measurements were also conducted on the cold-worked specimens. It was found that the observed changes in TEP and magnetic susceptibility induced by cold work were closely related to each and, in the cases of SS-304 and SS-347 that exhibited strongly increasing TEP with increasing cold work, martensitic phase transformation likely dominated the observed pattern of TEP versus cold work.

1. **Introduction**

A challenge of current interest to EPRI is NDE of microstructural evolution/damage in structural elements due to fast neutron irradiation induced embrittlement in austenitic stainless steel components [1]. The primary effects of irradiation are, besides possible void or cavity formation, irradiation-induced dislocation loops, defect clusters, and precipitates that exert significant impact on the mechanical properties and service performance of austenitic stainless steels [2]. The primary objectives of EPRI’s project are detection and quantitative assessment of chemical segregation and dislocation loop formation in the material. EPRI is pursuing a multi-modal approach involving various NDE methods in order to achieve the required sensitivity and selectivity for different degradation mechanisms to allow reliable estimates of remaining service life of reactor internals based on fracture mechanics. The thermoelectric power measurements conducted by UC are aimed at indirectly characterizing fracture properties in austenitic stainless steels. Additional magnetic permeability measurements were included to assess the role of martensitic phase formation caused by low-temperature plastic deformation that will be referred to as cold work in the following.

In order to avoid the need for working with highly radioactive materials, surrogate samples made of four types of austenitic stainless steel plate material (SS-304, SS-316, SS-347, and SS-A286) were provided by EPRI for these tests. The specimens were cold-rolled in a range of 0%-80% thickness reduction to simulate increasing dislocation density associated with fast neutron irradiation embrittlement. The cold-worked plates were subsequently machined into 0.5”-thick standard CT specimens. Table 1 lists the thirty-two cold-worked stainless steel specimens inspected in this study, where the cells indicate the number of specimens tested. From each material, four specimens were provided in order to establish the uncertainty due to in part to inherent sample to sample variations and in part to random experimental errors affecting the reproducibility of the measurements. The 32 CT specimens were characterized using both a commercially available two-point TE tester and an enhanced four-point TE inspection system developed at UC in collaboration with Imperial College of London and EPRI specifically for such applications [3]. In addition, the dynamic magnetic permeability of the specimens was tested to determine the level of ferromagnetic phase transformation caused by cold work.

Table 1 List of the thirty-two plastically deformed stainless steel specimens inspected in this study (each cell in the table indicates the number of specimens tested).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| material | cold work deformation | | | | |
| 0 % | 20 % | 40 % | 60 % | 80 % |
| SS-304 | 1 | 1 | 1 | 1 | 4 |
| SS-316 | 1 | 1 | 1 | 4 | 1 |
| SS-347 | 1 | 1 | 4 | 1 | 1 |
| SS-A286 | 1 | 4 | 1 | 1 | 1 |

In in Section 2, first the selected TEP measurement procedures will be described and then the obtained TEP results will be presented. Section 3 starts with a brief description of the equivalent ferrite content measurement used to determine the level of ferromagnetic phase transformation caused by low-temperature plastic deformation and then presents the obtained results in terms of relative magnetic susceptibility. Finally, Section4 summarizes the conclusions drawn from these results.

1. **TEP Measurements**

This project relied mainly on thermoelectric (TE) sensing of service-related degradation in critical metal components of nuclear energy systems while requiring only the simplest possible access in the form of four contact electrodes and minimal wiring while the material itself is used as the sensing element. Essentially all existing TE NDE techniques are based on the well-known Seebeck effect that is commonly used in thermocouples to measure temperature at the junction between two different conductors. Ideally, regardless of the temperature difference between the junctions, only thermocouples made of materials of different thermoelectric power will generate a thermoelectric voltage. This inherently differential nature makes TE inspection one of the most sensitive material discriminators used in NDE. Recent studies showed that TE techniques can be used to monitor corrosion, thermal and radiation embrittlement, plasticity, anisotropic texture, inhomogeneity and residual stresses and can be also exploited for nondestructive characterization of structural nuclear reactor components [3-11]. This unique sensitivity of TE inspection is exploited in this project for detection and quantitative characterization of service-related degradation in austenitic stainless steels used in nuclear reactors.

It should be mentioned that our original proposal submitted to and approved by EPRI stipulated only four-point TEP measurements that are far more accurate and reproducible than conventional two-point TEP measurements. The reason for this difference is that in the case of two-point measurements external heating is applied through the interface between the hot electrode and the specimen and the required substantial heat conduction through this inherently imperfect interface produces a significant uncertainty in the difference between the measured temperature and the specimen’s local temperature [12]. This is the same issue why four-point electric resistance measurements are significantly more accurate and reproducible than simpler two-point resistance measurements. However, four-point TEP measurements require larger surfaces to access the specimen under test and, because of the small size of the CT specimens used in this study, the custom-built system available at UC yielded only two independent measurement position on its left and right sides (after flipping sides, rotating the specimens proved to produce essentially the same results). In comparison, the “hot-tip” two-point TEP instrument used in this study measured the TEP in a relatively small heated spot on the surface of the specimen that could be manually scanned over the entire surface of the small CT specimens thereby allowing better spatial averaging of the somewhat inhomogeneous distribution of the sought material property. In order to take advantage of both the better accuracy and reproducibility of the automated four-point measurement system and the better spatial coverage allowed by manual scanning of the two-point instrument, both types of TEP measurement were included in this study.

**2.1 Two-point TEP Measurement Procedure**

Thermoelectric power measurements were conducted using a calibrated Walker Scientific ATS-6044T Alloy Sorter with a gold-plated probe. Although this instrument lacks computer control and access capability, an analog interface was added to it to facilitate electronic data transfer. Figure 1 shows a screenshot of the LabView data acquisition program used to collect the measured data with a PC. All readings were taken within a pre-set 1°F (0.6°C) wide temperature window centered around 170°F (77°C). As the hot tip of the instrument cools down during the measurement after pressing it against the specimen, multiple readings are taken over a 4-5 s interval. Data points falling outside the preset temperature window (red squares) are disregarded, while data points inside this range (white squares) are considered acceptable individual readings. A single set usually consists of 5-10 such individual readings taken at a given location on the specimen and 5-6 such contacts with the specimen are averaged for increased accuracy. This averaging suppresses random measurement uncertainties that are caused by electrical noise and temperature variations, but not those caused by variations in electrical and thermal contact resistance between the hot tip and the specimen and inherent TEP variations in inhomogeneous specimens. Twenty sets of readings were taken from each tested specimen at different locations representing about 500-600 total readings. In order to suppress local variations in TEP due to material inhomogeneity, the measurement positions were chosen randomly and the data was averaged.

Figure 2 shows a typical example of twenty readings from specimen SS-347-40-5 of 40% cold work,  average TEP,  standard deviation, and  estimated measurement error indicated by error bars. The recorded thermoelectric voltage (TEV) readings were converted into absolute TEP values using the linear calibration curve determined by measurements on four reference materials of known TEP values based on the following formula , where  and  are the experimentally determined calibration constants. The calibration materials included Alumel (–18.5 µV/°C), Ti-6Al-4V (–4.9 µV/°C), Copper (1.7 µV/°C), and Chromel 22.3 µV/°C).

**2.2 Two-point TEP Measurement Results**

Figure 3 shows the results of two-point TEP measurements versus cold work in four different types of stainless steel. Error bars represent measurement uncertainty levels calculated from the random variation of the measurements and the ±0.10 µV/°C estimated systematic error of the absolute calibration necessary to convert the actually measured thermoelectric voltage (TEV) and hot electrode temperature into TEP values. Two basic patterns can be observed in this data. First, the two austenitic stainless steel alloys that exhibit significant martensitic phase transformation under low-temperature plastic deformation, namely SS-304 and SS-347, exhibit significant increase in TEP from low TEP values of *S*0% = –1.57 and –1.34  µV/°C in intact state to high TEP values of *S*80% = –0.97 and –0.88  µV/°C in their most deformed state, respectively. Second, austenitic stainless steel alloys that exhibit very modest martensitic phase transformation, SS-316, or no such transformation at all, SS-A286, under low-temperature plastic deformation, exhibit relatively weak decrease in TEP from *S*0% = –1.53 to *S*80% = –1.61 µV/°C and from *S*0% = –1.28 to *S*80% = –1.37 µV/°C, respectively.

It is important to point out that for each type of stainless steel four specimens were made available for tests at one particular cold work level in order to establish the level of specimen-to-specimen variations at that cold work level (see Table 1). Within those four ensembles of four specimens each, representing a given combination of material type and cold work level, the average standard deviation was 0.04 µV/°C. In contrast, for the thirty-two specimens constituting the total ensemble of specimens the average standard deviation of the repeated TEP measurements was somewhat higher at 0.06 µV/°C, which indicates that the specimen-to-specimen variations were relatively modest with respect to the reproducibility of the manual two-point TEP measurements on each specimen. This conclusion is also supported by the results shown in Figure 3 that suggest that the specimen to-specimen variations were larger in those two types of material that undergo significant martensitic phase transformation during cold work. This increased variation is especially noticeable in SS-304 at 80% cold work level, where the specimen-to-specimen peak-to-peak variation of the TEP values is as high as 0.17 µV/°C while the standard deviation of TEP within the group is 0.08 µV/°C.

**2.3 Four-point TEP Measurement Procedure**

Thermoelectric power measurements were conducted using a custom-built four-point TEP measurement system that separates heat injection from the temperature and electric potential difference measurements [3]. For the purposes of heating, a 15 Ω/10 W power resistor was clamped on the CT specimens. The heating resistor was driven by a Stanford Research Systems CTC100 Temperature Controller that produced a harmonically changing output of 3 W peak power at a period of 30 minutes superimposed on a 3 W baseline power. The specimen was simultaneously tested on both its left (A) and right (B) sides by two pairs of high-precision “special limits of error” N-type thermocouples embedded in small copper pads. The temperature and electric potential differences between the sensing pads were monitored by an eight-channel Pico TC-08 Thermocouple Logger. Figure 4 shows a screen shot of the data acquisition and processing LabView software used for four-point TEP measurements. The sampling rate was set to 1 Hz and a new TEP reading was calculated and recorded in every thirty minutes, i.e., based on 1,800 sampling point. The measurements were run over six to twenty-four hours resulting in twelve to forty-eight measurement points at both locations. Figure 5 shows a typical example of thirty readings on two sides (A and B) of intact specimen SS-347-0-2 of  average TEP,  standard deviation, and  estimated measurement error indicated by error bars. It should be pointed out that the four-point TEP measurements were conducted at a lower average temperature of ≈35°C than the two-point TEP measurements made at ≈77°C.

**2.4 Four-point TEP Measurement Results**

Figure 6 shows the results of four-point TEP measurements versus cold work in four different types of stainless steel. Error bars represent measurement uncertainty levels calculated from the random variation of the measurements and the ±0.05 µV/°C estimated systematic error of the absolute TEP of the copper pads. The same two basic patterns can be observed in this data as in the case of the earlier described two-point TEP measurements. First, the two austenitic stainless steel alloys that exhibit significant martensitic phase transformation under low-temperature plastic deformation, namely SS-304 and SS-347, exhibit significant increase in TEP from low TEP values of *S*0% = –1.52 and –1.54  µV/°C in intact state to high TEP values of *S*80% = –0.92 and –0.76  µV/°C in their most deformed state, respectively. Second, austenitic stainless steel alloys that exhibit very modest martensitic phase transformation, SS-316, or no such transformation at all, SS-A286, under low-temperature plastic deformation, exhibit relatively weak decrease in TEP from *S*0% = –1.48 to *S*80% = –1.68 µV/°C and from *S*0% = –1.38 to *S*80% = –1.56 µV/°C, respectively.

As it was pointed out before, for each type of stainless steel four specimens were made available for tests at one particular cold work level in order to establish the level of specimen-to-specimen variations at that cold work level (see Table 1). Within those four ensembles of four specimens each, representing a given type of material and cold work level, the average standard deviation using four-point TEP measurements was 0.02 µV/°C. In contrast, for the thirty-two specimens constituting the total ensemble of specimens the average standard deviation of the repeated TEP measurements was somewhat higher at 0.03 µV/°C, which indicates that the specimen-to-specimen variations were again relatively modest even with respect to the better reproducibility of four-point TEP measurements on each specimen. This conclusion is also supported by the results shown in Figure 6 that suggest that the specimen to-specimen variations were larger in those two types of material that undergo significant martensitic phase transformation during cold work. Again, this variation is especially noticeable in SS-304 at 80% cold work level, where the specimen-to-specimen peak-to-peak variation of the TEP values is as high as 0.08 µV/°C while the standard deviation of TEP within the group is only 0.03 µV/°C.

**2.5 Comparison of Two- and Four-point TEP Results**

As it was stated earlier, the reason for conducting both two- and four-point TEP measurements was to exploit the relative advantages of these two techniques over each other. Conventional two-point TEP measurements offer lower accuracy and reproducibility but faster measurement speed and superior spatial resolution for inhomogeneous TEP distributions than their more sophisticated four-point counterparts. These differences were also perceivable in the experimental results shown in Figures 3 and 6, but a more quantitative assessment of this relationship necessitates direct comparison of the two data sets. For this purpose, Figure 7 shows the correlation between two- and four-point TEP measurement results at five different cold work levels in four different types of stainless steel. The slope of the linear regression line in red indicates that the four-point TEP results are on the average 4% higher than the corresponding two-point TEP results. Part of this difference could be attributed to the non-negligible temperature difference of TEP in austenitic stainless steels since the average measurement temperatures were slightly different at ≈77°C for the two-point measurements and ≈35°C for the four-point measurements. However, this difference could be also at least partially due to the indirect absolute calibration used for the two-point TEP measurement. The modest coefficient of determination  is caused by the fact that the cold-work induced TEP changes are inherently small relative to the measurement uncertainties of both techniques. However, it is clear from Figure 7 that the measurement uncertainty of the two-point technique (horizontal error bars) is significantly higher than that of the four-point technique (vertical error bars). It should be mentioned that this difference in measurement uncertainty could be significantly higher except that the CT specimens were precision machined and lacked any adverse effects, such as surface roughness, oxidation, or contamination, that usually interfere with two-point TEP measurements.

Based on the relatively close correlation found between the results of the two- and four-point TEP measurements, it is reasonable to assume that the best TEP estimate over the entire volume of these CT specimens is the average of the two sets of results. Figure 8 shows the averaged two- and four-point TEP values versus cold work in four different types of stainless steel. In the next section this average TEP value will be correlated with the magnetic susceptibility of the thirty-two CT specimens.

1. **Equivalent Ferrite Content (EFC) Measurement**

Numerous magnetic, electric, ultrasonic and thermoelectric methods could be exploited for the purposes of microstructural evolution in austenitic stainless steel components including fracture-critical nuclear reactor plant components. However, most of these NDE methods, if not all of them, are sensitive and can be potentially overwhelmed by martensite formation that is not directly related to the microstructural changes of primary interest. The main problem is that martensite formation under plastic deformation is exceptionally strongly temperature dependent and this dependence renders the degree of martensite formation highly variable [11, 13]. Therefore, magnetic susceptibility measurements were also included in this primarily thermoelectric NDE project so that the role of ferromagnetic martensitic phase transformation in the measured TEP changes could be assessed.

**3.1 EFC Measurement Procedure**

An MP30E-S Fischer Technology Feritscope was used to measure the equivalent ferrite content (EFC or %Fe) of the specimens [14]. The operation of this instrument is based on low-frequency (1.8 kHz) dynamic magnetic permeability measurement. The Feritscope was calibrated using reference blocks of 11.8 %Fe and 31.0 %Fe values. The EFC reading can be empirically related to the magnetic susceptibility χ or the relative magnetic permeability  of strongly paramagnetic and ferromagnetic steels using a quadratic regression polynomial χ ≈ 0.06 × %Fe + 0.0194 × %Fe2 based on experimental data published by Yin *et al.* [15]. This is a relatively easy and fast test that is well suited for the purposes of comparison to the two- and four-point TEP data. Fifty readings were taken from each specimen to increase the reliability and accuracy of the collected data by averaging. It should be mentioned that the MP30E-S has a threshold sensitivity of %Fe ≈ 0.5%, that corresponds to a magnetic susceptibility value of χ ≈ 0.035, and below this threshold value the instrument does not trigger a reading at all. Since the A286 stainless steel alloy does not exhibit any ferromagnetic behavior even at 80% plastic deformation, eddy current testing was used to determine the magnetic susceptibility of the specimens. For this purpose, a Nortec 2000D eddy current instrument was used with a broadband (300 Hz-10 kHz) pancake probe at 150 Hz. When such a probe is used below its low-frequency cut-off on a paramagnetic specimen, the result is mainly sensitive to its magnetic permeability and much less to its electric conductivity. In order to get an approximate value for the absolute magnetic susceptibility of the A286 CT specimens, the sensitivity of the above described eddy current measurement configuration was calibrated on one of the strongly paramagnetic stainless steel samples (SS-347-40-03) whose magnetic susceptibility was determined earlier by the Feritscope as χ = 1.11 ± 0.05.

**3.2 EFC Measurement Results**

Figure 9 shows the measured magnetic susceptibility as a function of cold work in four different types of stainless steel. Error bars represent the maximum positive and negative deviation from the average among fifty readings by the MP30E-S Feritscope. The same two basic patterns observed in the TEP data are evident in this data as well. First, the two austenitic stainless steel alloys that exhibit significant martensitic phase transformation under low-temperature plastic deformation, namely SS-304 and SS-347, exhibit significant increase in magnetic susceptibility from low values of χ0% = 0.12 and 0.02 in intact state to high values of χ80% = 4.1 and 6.4 in their most deformed state, respectively. SS-316 austenitic stainless steel exhibits very modest martensitic phase transformation under low-temperature plastic deformation with the magnetic susceptibility increasing from χ0% = 0.04 to χ80% = 0.25, while SS-A286, which exhibits no such phase transformation at all, has a very low and essentially constant magnetic susceptibility of χ = 0.01 independent of its cold work level.

The above results indicate that the observed cold work induced changes in thermoelectric power and magnetic susceptibility are closely related, an assumption that can be easily tested by directly correlating these two NDE parameters to each other. Figure 10 shows the measured magnetic susceptibility versus the averaged two- and four-point TEP values for five levels of cold work in four different types of stainless steel. There is an obvious correlation that is qualitatively indicated by the black trend line. The only exception from this correlated behavior is stainless steel A286 that does not exhibit any perceivable ferromagnetic phase transformation, therefore its magnetic susceptibility is very low and essentially constant, while its TEP still changes in a measurable way.

1. **Conclusions**

Thirty-two specimens made of four types of austenitic stainless steel plate material (SS-304, SS-316, SS-347, and SS-A286) that were first cold-rolled in a range of 0%-80% thickness reduction to simulate increasing dislocation density associated with fast neutron irradiation embrittlement and were subsequently machined into 0.5”-thick CT specimens. Each specimen was tested by two different thermoelectric and one magnetic nondestructive materials characterization techniques. The two thermoelectric techniques included a commercially available two-point TEP instrument (Walker Scientific ATS-6044T Alloy Sorter) and a four-point TEP measurement system developed at UC based on a Stanford Research Systems CTC100 Temperature Controller and an eight-channel Pico TC-08 Thermocouple Logger. The first technique allowed highly localized “hot-spot” measurements with good spatial resolution even on these relatively small CT specimens, but with limited reproducibility and absolute accuracy. In contrast, the second technique offered higher repeatability and absolute accuracy, but only very limited (left side/right side) spatial resolution.

Both series of thermoelectric measurement yielded essentially the same trends for the changes in TEP with cold work. The two austenitic stainless steel alloys that were known to undergo significant martensitic phase transformation during low-temperature plastic deformation, namely SS-304 and SS-347, exhibited relatively strongly increase in TEP with increasing cold work (*S*80% – *S*0% ≈ +0.7 µV/°C). In contrast, the other two alloys that experience very modest or no martensitic phase transformation due to plastic deformation, namely SS-316 and SS-A286, exhibited a weaker decrease in TEP with increasing cold work (*S*80% – *S*0% ≈ –0.2 µV/°C). Phase transformation of paramagnetic austenitic grains into ferromagnetic martensitic ones causes a significant increase of magnetic susceptibility in otherwise weakly paramagnetic austenitic stainless steels, therefore magnetic susceptibility measurements were also conducted on the cold-worked specimens using an MP30E-S Fischer Technology Feritscope that measures the dynamic permeability of the specimen under test and displays the results in terms of equivalent ferrite content (EFC). For better comparison with other magnetic measurements, the EFC readings were converted into magnetic susceptibility values using an empirical calibration technique well known in the scientific literature. The results showed that the observed cold work induced changes of TEP and magnetic susceptibility were closely correlated to each other. In the cases of SS-304 and SS-347 specimens, which exhibited substantial TEP increase with increasing cold work, it is likely that martensitic phase transformation dominated the observed pattern of TEP versus cold work.

It has been pointed out before that strong martensitic phase transformation might partially or fully overshadow other changes in some austenitic stainless steels that otherwise could be used for nondestructive characterization of their microstructure. The main reason for this is that NDE measurements will exhibit rather high variability because the dominating phase transformation effect itself is strongly temperature dependent and therefore the degree of martensite formation is highly variable [11, 13]. Since the actual problem of interest to EPRI is identifying NDE techniques capable of characterizing changes in relevant microstructural features of structural elements due to fast neutron irradiation induced embrittlement in austenitic stainless steel components, the problem of ferromagnetic phase transformation might be avoided in the future if the results of this study are incorporated into the planning phase of sample preparation. The primary effects of irradiation are void/cavity formation, irradiation-induced dislocation loops, defect clusters, and precipitates that exert significant impact on the mechanical properties and service performance of austenitic stainless steels. Specifically, the stated objectives of the current EPRI project were detection and quantitative assessment of chemical segregation and dislocation loop formation in the material. Cold work was applied only to produce representative surrogate samples in order to avoid the need for working with highly radioactive materials. Therefore, it is recommended that specimens made of austenitic stainless steels, such as SS-304 and SS-347, that are susceptible to ferromagnetic martensite formation under cold work should be plastically deformed at slightly elevated temperatures, say at 60-80°C, where the degree of such phase transformation is approximately two orders of magnitude lower.

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17. **Figures**



Figure 1 Data acquisition and processing LabView software used for two-point TEP measurements.



Figure 2 A typical example of twenty readings from specimen SS-347-40-5 (40% cold work, TEP average = –1.23 µV/°C, TEP standard deviation = 0.067 µV/°C, error bars represent ±0.1 µV/°C estimated measurement error).



Figure 3 The results of two-point TEP measurements versus cold work in four different types of stainless steel.



Figure 4 Data acquisition and processing LabView software used for four-point TEP measurements.



Figure 5 A typical example of thirty readings on two sides from specimen SS-347-0-2 (no cold work, TEP average = –1.53 µV/°C, TEP standard deviation = 0.004 µV/°C, error bars represent ±0.02 µV/°C estimated measurement error).



Figure 6 The results of four-point TEP measurements versus cold work in four different types of stainless steel.



Figure 7 Comparison between two- and four-point TEP measurement results at five different cold work levels in four different types of stainless steel.



Figure 8 Averaged two- and four-point TEP values versus cold work in four different types of stainless steel.



Figure 9 The results of magnetic susceptibility measurements versus cold work in four different types of stainless steel.



Figure 10 Magnetic susceptibility versus averaged TEP for five levels of cold work in four different types of stainless steel.