Chapter 16
Repeatability of Contour Method Residual Stress Measurements for a Range of Material, Process, and Geometry

Mitchell D. Olson, Adrian T. DeWald, and Michael R. Hill

Abstract This paper examines precision of the contour method using five residual stress measurement repeatability studies. The test specimens evaluated include: an aluminum T-section, a stainless steel plate with a dissimilar metal slot-filled weld, a stainless steel forging, a titanium plate with an electron beam slot-filled weld, and a nickel disk forging. These specimens were selected to encompass a range of typical materials and residual stress distributions. Each repeatability study included contour method measurements on five to ten similar specimens. Following completion of the residual stress measurements an analysis was performed to determine the repeatability standard deviation of each population. In general, the results of the various repeatability studies are similar. The repeatability standard deviation tends to be relatively small throughout the part interior and there are localized regions of higher repeatability along the part perimeter. The repeatability standard deviations over most of the cross-section range from 5 MPa, for the aluminum T-section, to 35 MPa, for the stainless steel forging. These results provide expected precision data for the contour method over a broad range of specimen geometries, materials, and stress profiles.

Keywords Repeatability • Repeatability standard deviation • Measurement repeatability • Precision • Contour method • Residual stress

16.1 Introduction

Precision is an important parameter to consider when selecting a measurement technique since it provides the expected measurement variability for a given test method. The definition of precision is the closeness of agreement between independent test results obtained under stipulated conditions. Precision is closely related to measurement repeatability. Repeatability is the precision where the stipulated conditions require the same test method applied to identical test specimens, in the same laboratory, by the same operator, over a short interval of time [1]. Repeatability is quantified by the repeatability standard deviation, which is simply the standard deviation of test results from a repeatability study.

The repeatability of the contour method has been determined in prior publications in a quenched aluminum bar [2] and a stainless steel plate with a stainless steel slot-filled weld [3]. The repeatability study in the quenched aluminum bar found a stress field that had large magnitude compressive stress along the bar periphery (around −175 MPa) and tensile stress at the center of the bar (around 175 MPa). The repeatability standard was between 5 and 10 MPa over most of the cross-section, with localized regions and the periphery having larger repeatability standard deviations (maximum as large as 20 MPa). The repeatability study in the stainless steel plate found repeatability standard deviations under 20 MPa at most locations with localized regions up to 30 MPa.

The primary objective of the present study is to build on the prior studies [2, 3] and determine contour method repeatability under a representative set of conditions. The set of conditions includes alloys of iron, aluminum, titanium, and nickel, reflecting key industrial alloys. The set of conditions also includes a range of geometry, including plate, disk, and tee-section.

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16.2 Methods

16.2.1 Overview

Contour method repeatability was assessed in five different configurations: an aluminum T-section, a stainless steel plate with a dissimilar metal (DM) slot-filled weld, a stainless steel forging, a titanium plate with an electron beam (EB) slot-filled weld, and a nickel alloy disk. Each repeatability assessment included contour method measurements on sets of replicate specimen and statistical analysis to determine the repeatability standard deviation for each set. Since the contour method is a destructive measurement technique that requires physically cutting the specimen in half (details below), it is impossible to repeatedly measure the same specimen. Thus, a set of specimen was prepared for each configuration and care was taken to obtain specimens with consistent residual stress distributions. The following is a brief description of each specimen type.

16.2.2 Geometry and Material

16.2.2.1 Aluminum T-Section

Aluminum T-section specimens were fabricated from bars cut from 79.38 mm (3.125 in) thick 7050-T7451 aluminum plate that had been stress relieved by stretching. The bars had a length of 762 mm (30.0 in), a height of 79.38 mm (3.125 in), and a width of 82.55 mm (3.25 in). The bars were heat treated, including a quench, to induce high residual stress indicative of the -T74 temper. The heat treatment used the recipe described in [4] that consists of heating the specimens to 477 °C (890 °F) for 3 h, quenching in room temperature water, artificial aging at 121 °C (250 °F) for 8 h followed by additional aging at 177 °C (350 °F) for 8 h. T-sections were then machined from the bars to represent an airframe structural member. Each T-section had a length of 254 mm (10.0 in), a height of 50.8 mm (2.0 in), a width of 82.55 mm (3.25 in), and a leg thicknesses of 6.35 mm (0.25 in), as shown in Fig. 16.1.

16.2.2.2 Stainless Steel DM Welded Plate

Stainless steel dissimilar metal (DM) weld specimens were fabricated from one long plate made of high-strength 316 L stainless steel. The plate had a 25.4 mm (1.0 in) by 152.4 mm (6.0 in) cross-section and a length of 1.22 m (48.0 in). A slot was machined along the entire length of the plate with a depth of 9.53 mm (0.375 in), a width of 19.05 mm (0.75 in), and a 70° root angle. The slot and plate cross-section can be seen in Fig. 16.2. Prior to filling the slot with weld material, the plate was constrained by welding the plate to an additional support plate. The weld joining the plate to the support plate was a continuous 7.94 mm (0.313 in) fillet weld that was applied along both 1.22 m edges of the plate. The slot weld was made using eight passes, each continuous along the entire length of the plate using an automated welder of 0.89 mm (0.035 in) diameter A52M (ERNiCrFe-7A) wire. Welding was gas tungsten arc welding (GTAW) with 250 A current, 10.5 V voltage, and 101.6 mm/min (4 in/min) travel speed.

Following welding, the fillet welds were machined away to release the DM welded plate from the support plate and the ends of the DM welded plate were removed to eliminate the inconsistent weld bead geometry at the start and stop of the weld (139.7 mm (5.5 in) of material was removed from the weld start and 63.5 mm (2.5 in) was removed from the weld stop). The remaining section was 1.02 m (40.0 in) long.

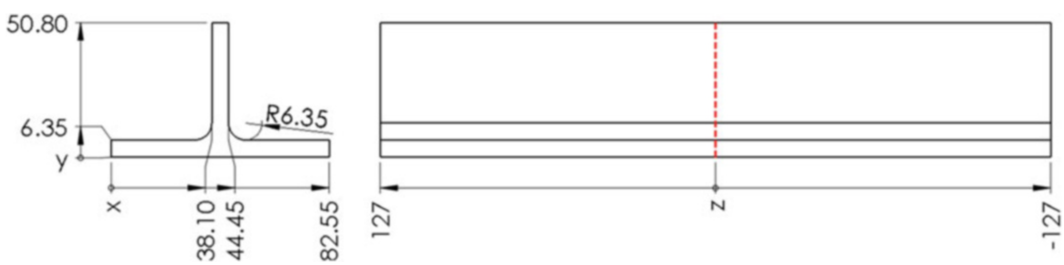

Fig. 16.1 Aluminum T-section dimensions and measurement location (dimensions in mm)

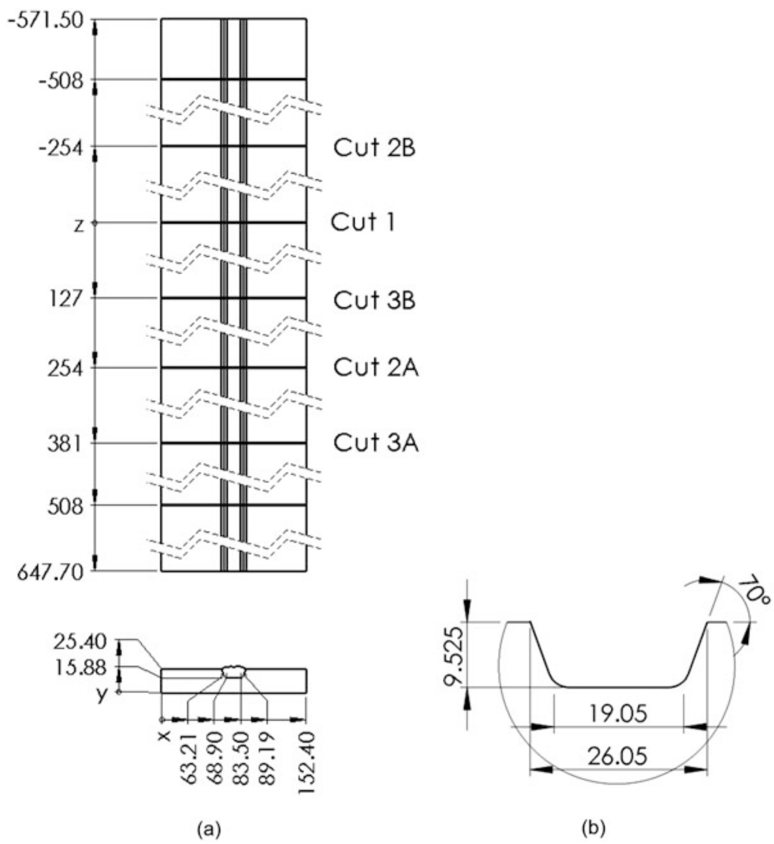

Fig. 16.2 Stainless steel dissimilar metal (**a**) dimensions and measurement locations and (**b**) slot details (dimensions in mm)

16.2.2.3 Titanium Electron Beam Welded Plate

Titanium alloy electron beam (EB) welded plate specimens were fabricated using one long Ti-6Al-4 V plate, with similar geometry to the stainless steel DM welded plate (same cross-section and slot dimensions). The weld process is a typical additive manufacturing process, but service parts would typically be subjected to thermal stress relief. The groove was filled along the entire length of the plate with 8-passes of 3.18 mm (0.125 in) diameter Ti-6Al-4 V wire. After completion of the weld, the plate was sectioned into 101.6 mm (4.0 in) long pieces, as shown in Fig. 16.3.

16.2.2.4 Stainless Steel Forging

Stainless steel forging specimens in 304 L are roughly hemi-spherical with an outer diameter of 73.7 mm (2.9 in). They include a forged internal cavity with inner diameter of 30.5 mm (1.2 in), and a height of 50.8 mm (2.0 in) (Fig. 16.4). The specimens were produced using a multi-stage forging process. The specimen billets were heated to 980 °C (1800 °F) for 60 min, die pressed to 75% of their original height in a hydraulic press, cooled to room temperature, heated to 1750 °F for 60 min, and subjected to a high-energy rate forging operation. Next, the specimens were cooled to room temperature, annealed at 955 °C (1750 °F) for 30 min, and then water quenched. The final processing steps consisted of reheating the specimens to 845 °C (1550 °F) for 60 min, a final high-energy rate forging operation, followed by a final water quench.

16.2.2.5 Nickel Alloy Disk

Nickel alloy (Udimet-720Li) disk specimens had a diameter of 151.20 mm (5.95 in) and a maximum height of 70.41 mm (2.77 in), as is shown in Fig. 16.5. The specimens were forged and heat treated, including a quench, to achieve desired mechanical properties. The heat treatment consisted of pre-heating the specimens to 1080 °C (1975 °F), forging to the

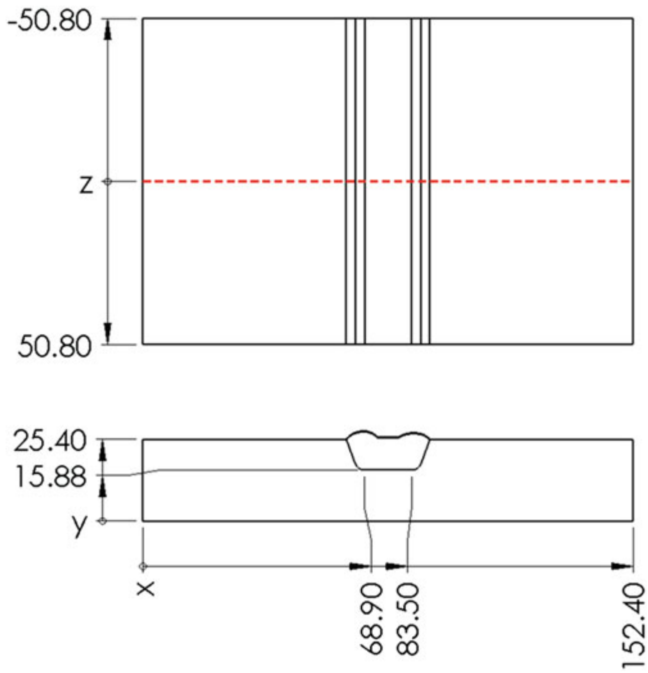

Fig. 16.3 Titanium electron beam welded plate dimensions and measurement location (dimensions in mm)

nominally finished shape, solution heat treating at 1105 °C (2020 °F), and oil quenching. The specimens were then stabilized at 760 °C (1400 °F) for 8 h, air cooled, aged at 650 °C (1200 °F) for 24 h and then air cooled to room temperature. Since the amount of available material was limited, three disks were sectioned in half to give six nominally identically half disk specimens.

16.2.3 Contour Method

The contour method is a residual stress measurement technique whose theoretical basis was established by Prime [5]. A contour method measurement will cut a part along a given measurement plane and deformation of the cut surfaces will occur as a direct result of residual stress release and redistribution. The resulting deformed cut surface profiles can be measured and when the negative of the measured surface profiles are applied as a displacement boundary condition in a finite element model of the half part, the residual stress released normal to the cutting plane can be determined. Detailed experimental steps for the contour method have been provided by Prime and DeWald [6].

The contour method measurements for each repeatability study followed nominally the same procedure with a summary given here. For each contour method measurement, the specimen was cut in two using a wire electric discharge machine (EDM) while the specimen was rigidly clamped to the EDM frame. Following cutting, the profile of each of the two opposing cut faces was measured with a laser scanning profilometer to determine the surface height normal to the cut plane as a function of in-plane position. Surface height data were taken on a grid of points with spacing between 100 and 200 μm in each direction. The two cut surface profiles were then aligned, averaged on a common grid, and the average was fit to a smooth bivariate analytical function. The residual stress release on each measurement plane was found by applying the negative of the smoothed surface profile as a boundary condition on the cut face of a linear elastic finite element model of the cut part. Each model used the corresponding set of elastic material properties given in Table 16.1.

16.2.4 Repeatability Experiments

For each of the five specimen types described above, a contour method repeatability experiment was performed. The repeatability studies involved performing a single contour method measurement on a set of similar test specimens. Each

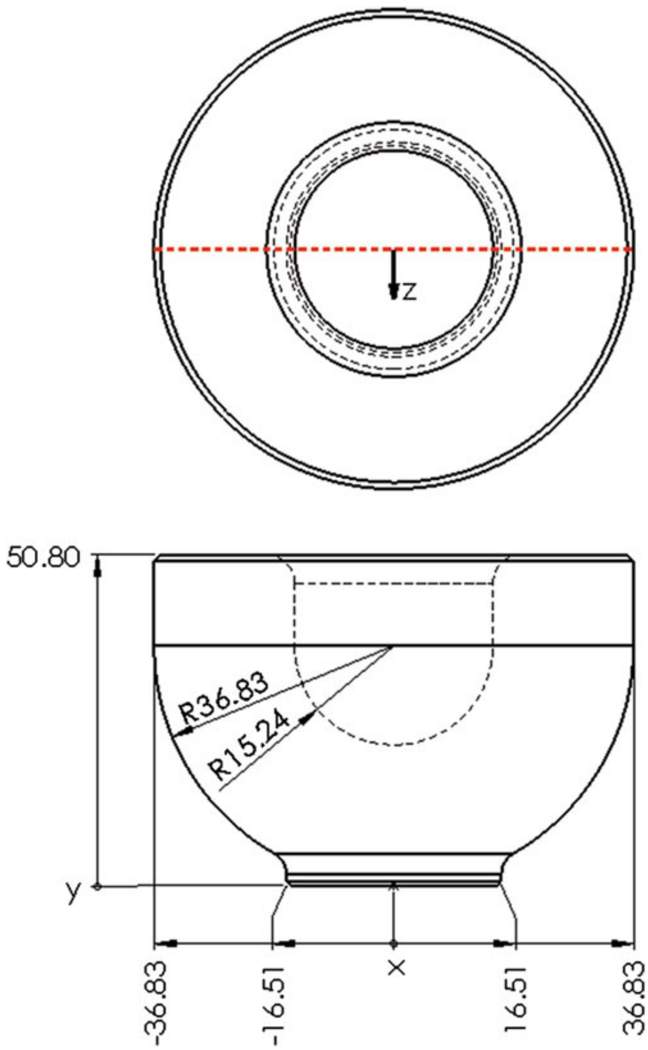

Fig. 16.4 Stainless steel forging dimensions and measurement location (dimensions in mm)

measurement provided a 2D map of residual stress. All measurements were performed in a consistent manner to assess measurement repeatability. The following is a brief description of the measurements performed on each set of specimens.

For the aluminum T-section specimens, contour method measurements were performed at the mid-length of ten specimens (127 mm (5 in) from each end, as shown in Fig. 16.1). Six titanium welded specimens were measured at the plate mid-length, as shown in Fig. 16.3. The contour method measurements on the stainless steel forgings were performed at the specimen mid-width (shown in Fig. 16.4) for six specimens. For the six nickel alloy (half) disk specimens, contour method measurements were performed at the specimen mid-width (shown in Fig. 16.5). Stress release from sectioning the disks in half was found using a supplemental stress analysis in conjunction with the strain change recorded before and after sectioning (using strain gages at multiple locations). The total hoop stress, including the effect of sectioning, is reported for the disk specimens.

The stainless steel DM weld repeatability study consisted of measurements at different positions along the length of the plate, rather than making measurements in nominally identical specimens removed from the long plate. This was done to preserve the original residual stress field present in the plate, which is more representative of a highly constrained weld employed at pressurized water reactor (PWR) nuclear power plants. The repeatability experiment consisted of five contour method measurements, where each measurement repeatedly cut the plate in half. Figure 16.2 show that the first measurement (Cut 1) cut the plate in half; the second (Cut 2A) and third measurements (Cut 2B) cut each of the half plates in half; and the fourth (Cut 3A) and fifth measurements (Cut 3B) cut two of the quarter plates in half. Corrections were made to account for the small changes in residual stress as the specimen size was reduced by previous contour measurements. The corrections used the data from prior contour method measurements at the subsequence measurement plane was as done in [7].

Fig. 16.5 Nickel disk dimensions and measurement location (dimensions in mm)

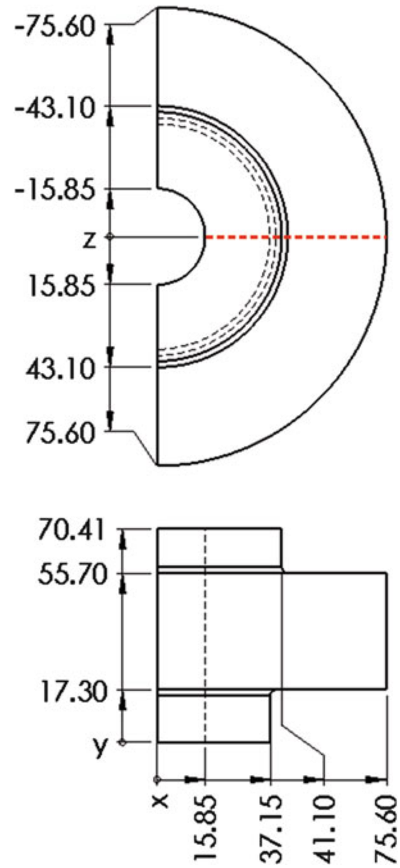

Table 16.1 Material properties for each of the specimens used in the repeatability studies

Specimen	Elastic modulus (GPa)	Poisson's ratio	Yield strength (MPa)
Aluminum T-section (7085-T74)	71	0.33	460
Titanium EB welded plate (Ti-6Al-4V)	110	0.31	960
Nickel disk (Udimet-720Li)	200	0.31	300–500
Stainless steel forging (304 L)	200	0.249	210
Stainless steel DM welded plate (316 L plate)	203	0.3	440
Stainless steel DM welded plate (A52 weld)	211	0.289	345–482

Following completion of the contour method measurements the mean and repeatability standard deviation were calculated for each repeatability experiment using standard formulae. This provides a mean 2D stress map and a 2D map of the repeatability standard deviation.

16.3 Results

Residual stress 2D maps of mean and repeatability standard deviation for all configurations are shown in Figs. 16.6, 16.7, 16.8, 16.9, 16.10, 16.11, 16.12, 16.13, 16.14, and 16.15. The median, mean, 75th percentile, 95th percentile, and maximum value of the repeatability standard deviation for all configurations is tabulated in Table 16.2.

The mean longitudinal residual stress in the aluminum T-section has compressive stress at the left and right edges of the bottom flange (minimum value of approximately −240 MPa) and at the top of the center flange (minimum value of approximately −70 MPa) with tensile stress at the intersection of the bottom and center flanges (peak value of approximately 100 MPa) (Fig. 16.6a). The measured residual stress is similar between the ten measurements as is indicated by the repeatability standard deviation (Fig. 16.6b) and the line plots (Fig. 16.7). The repeatability standard deviation is low at most

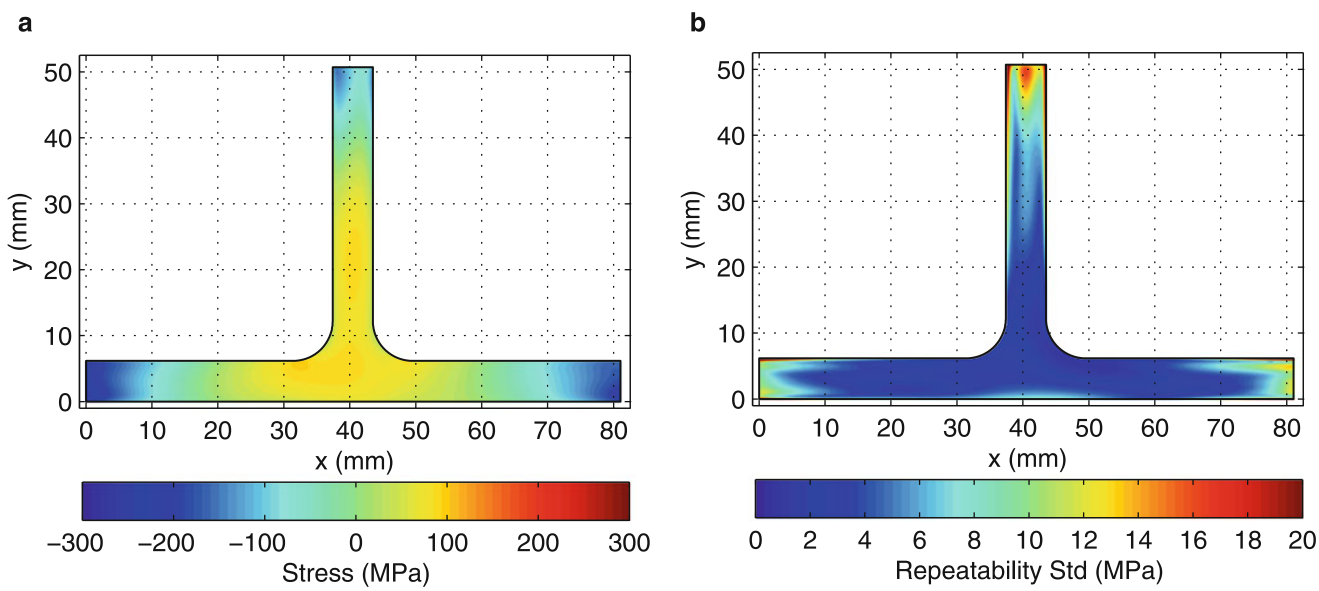

Fig. 16.6 (**a**) Mean and (**b**) repeatability standard deviation for the aluminum T-section specimens

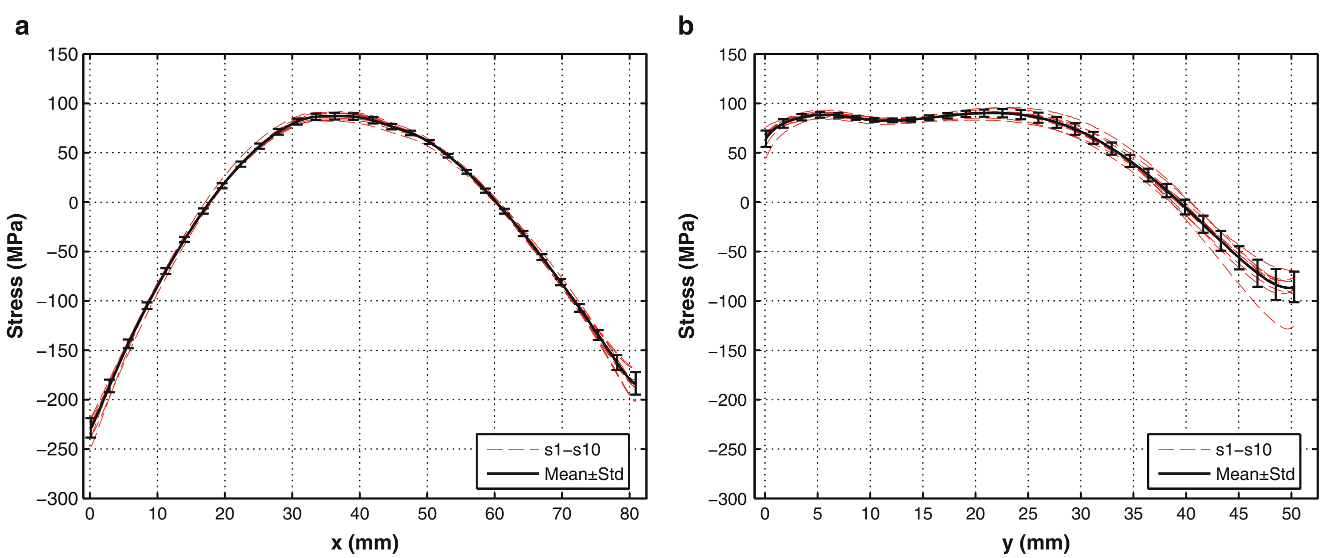

Fig. 16.7 *Line* plots of individual measurements (*dashed*) and the mean and repeatability standard (*solid black*) for the aluminum T-section samples along the (**a**) x-direction at y = 3.18 mm and (**b**) along the y-direction at x = 40.52 mm

points (average of 5 MPa), but with localized regions at the edges of the bottom and center flanges where the repeatability standard deviations is larger (95th percentile at 13 MPa).

The mean longitudinal residual stress in the stainless steel DM welded plate has tensile stress in the weld area and heat-affected zone (maximum value of approximately 380 MPa) and near the left and right edges of the plate where the plate was welded to the support fixture (maximum value of approximately 400 MPa) (Fig. 16.8a). There is compensating compressive stress toward the top of the plate at the left and right edges (minimum value of approximately −260 MPa). The stress line plots for each individual measurement and the mean (Fig. 16.9) show that the stress in nominally consistent between specimen, with modest differences at the top and bottom of the plate. Most points had low repeatability standard deviations (average of 17 MPa), but there are localized regions near the part boundary where the repeatability standard deviation is larger (95th percentile at 36 MPa), as shown in Fig. 16.8b.

The mean longitudinal stress in the titanium EB welded plate has tensile stress in the weld area (maximum value of approximately 350 MPa) and compensating compressive stress in the heat-affected zone (minimum value of approximately −200 MPa) (Fig. 16.10a). The line plots in Fig. 16.11 show that the stress is very consistent between each specimen. Most

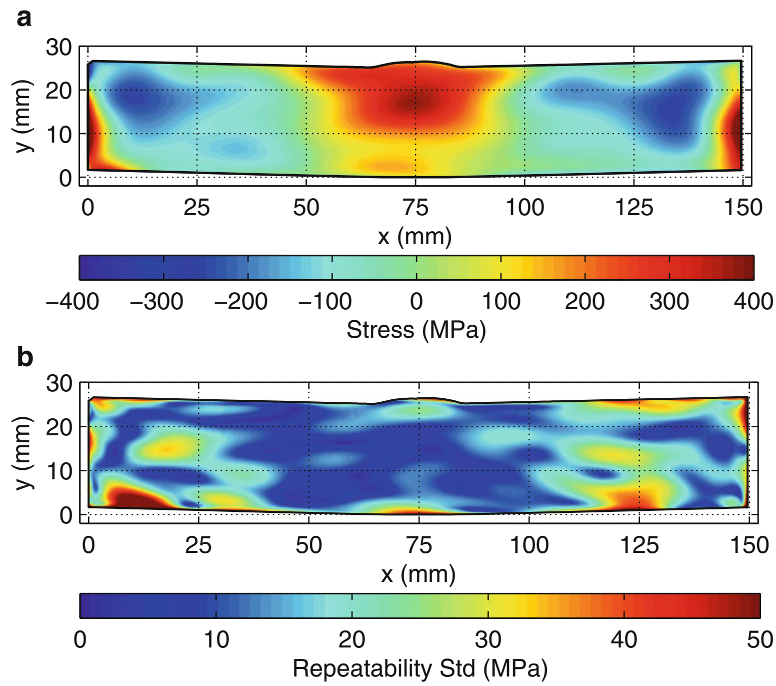

Fig. 16.8 (**a**) Mean and (**b**) repeatability standard deviation for the stainless steel DM welded specimens

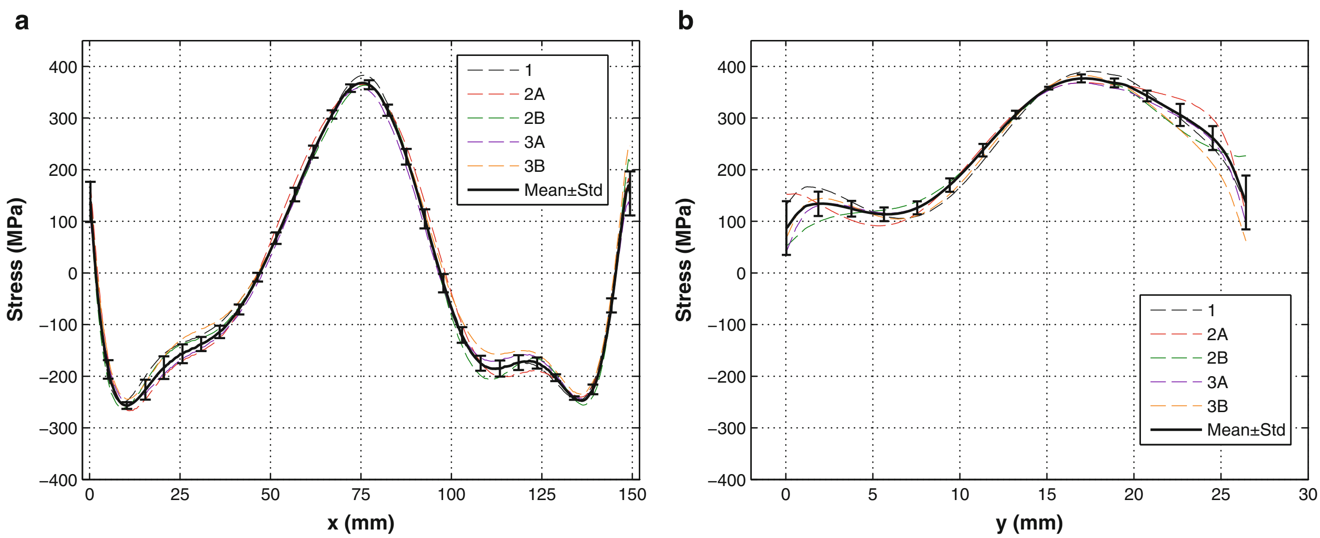

Fig. 16.9 *Line* plots of individual measurements (*dashed*) and the mean and repeatability standard (*solid black*) for the stainless steel DM welded samples along the (**a**) x-direction at y = 19.05 mm and (**b**) along the y-direction at x = 76.2 mm

points had a low repeatability standard deviation (average of 8 MPa), with localized regions near the part boundary having higher repeatability standard deviations (95th percentile at 17 MPa), as shown in Fig. 16.10b. In this case, the repeatability standard deviation appears to be more spatially uniform over the cross-section than was found in other cases.

The mean hoop stress in the stainless steel forging has tensile stress adjacent to the internal cavity (maximum value of approximately 340 MPa) and compensating compressive stress near the outer surfaces of the forging (minimum value of approximately −260 MPa) (Fig. 16.12a). Five of the six measurements were nominally consistent, with one being a significant outlier (maximum tensile stress was approximately 100 MPa larger than all the other measurements) as is shown in Fig. 16.13. To further illustrate the outlying measurement, line plots of the stress measured in all six specimens are shown in Fig. 16.14. The repeatability standard deviation reported in Fig. 16.12b, which omits the outlier measurement, has a low repeatability standard deviation (mean at 24 MPa) with localized regions having higher repeatability standard deviations

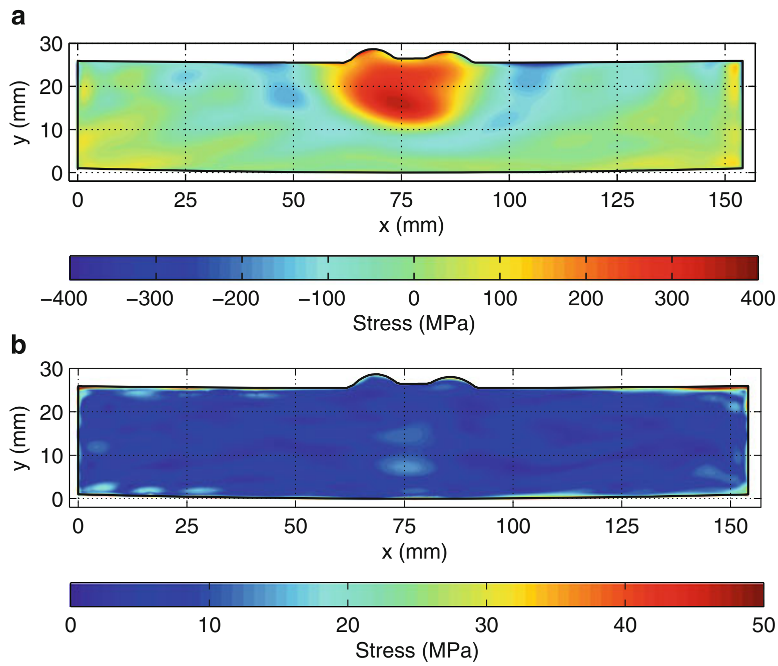

Fig. 16.10 (**a**) Mean and (**b**) repeatability standard deviation for the titanium EB welded plate specimens

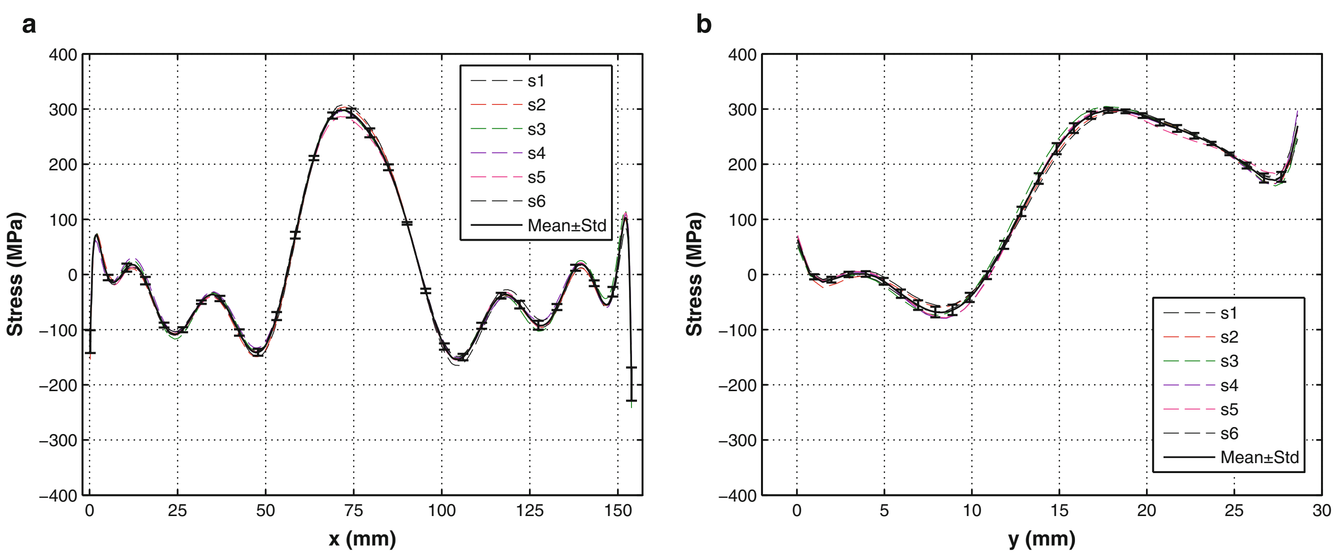

Fig. 16.11 *Line* plots of individual measurements (*dashed*) and the mean and repeatability standard (*solid black*) for the titanium EB welded plate samples along the (**a**) x-direction at y = 20.32 mm and (**b**) along the y-direction at x = 68.15 mm

(95th percentile at 52 MPa). (The repeatability standard deviation including the outlier measurement us larger, with values up to 135 MPa near the forging cavity).

The mean hoop stress in the nickel disk has tensile stress towards the disk inner diameter at mid-thickness (maximum value of approximately 450 MPa) and compensating compressive stress toward the disk periphery (minimum value of approximately −580 MPa) (Fig. 16.15a). Line plots (Fig. 16.16) show that the measurements are consistent relative to magnitude of stresses being measured. The repeatability standard deviation distribution is consistent with those from the other configurations, but with more spatial variation over the cross-section. Most points have a modest repeatability standard deviation (average of 25 MPa) and localized regions of high repeatability standard deviation (95th percentile at 52 MPa) particularly near the top and bottom of the disk (Fig. 16.15b).

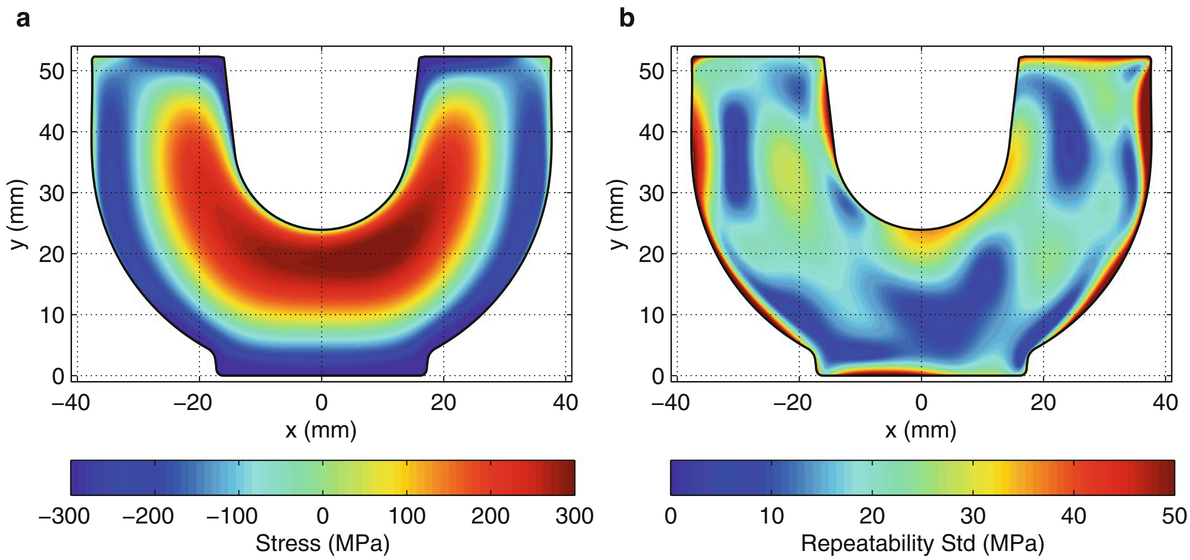

Fig. 16.12 (**a**) Mean and (**b**) repeatability standard deviation for the stainless steel forging specimens

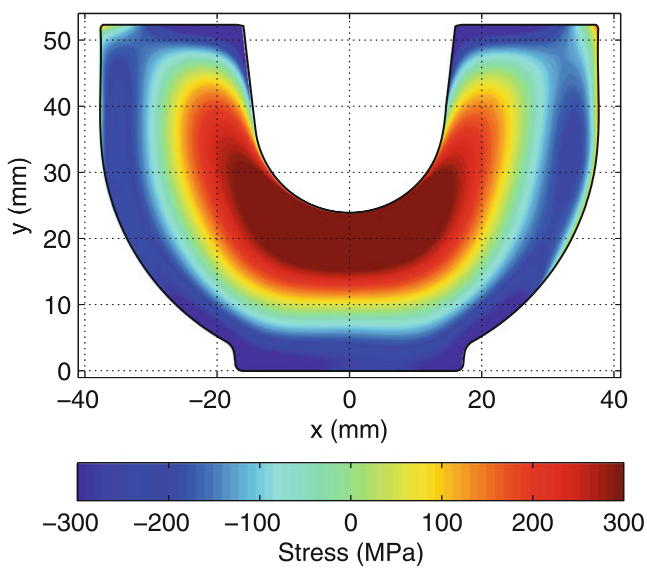

Fig. 16.13 Outling stainless steel forging measurements (S2)

16.4 Discussion

The present repeatability experiments provide similar results to those reported in earlier work [2, 3]. In the study using aluminum bars [2], both the measured stress and the repeatability standard deviation was very similar to the results found in the present aluminum T-section. The repeatability standard deviation was below 10 MPa at most points with maximum values near the part perimeter at 20 MPa for both parts. Similarly, in a study using a stainless steel plate with a stainless steel slot-filled weld [3], the repeatability standard deviation was below 20 MPa at most points, which is very close to the values found in the stainless steel DM welded plate reported here.

The repeatability standard deviation trend found among the five configurations is consistent. There tends to be relatively stable and low magnitude repeatability standard deviation over most of the specimen interior and localized regions of higher variability along the part perimeter. The magnitude of the repeatability standard deviation increases with elastic modulus of the material, as shown in Fig. 16.17a. The materials with the largest elastic moduli also have the largest repeatability standard deviation and alternatively materials with lower elastic moduli have smaller repeatability standard deviations. To better interpret the results, the mean, median, 75th percentile, and 95th percentile of the repeatability standard deviation for

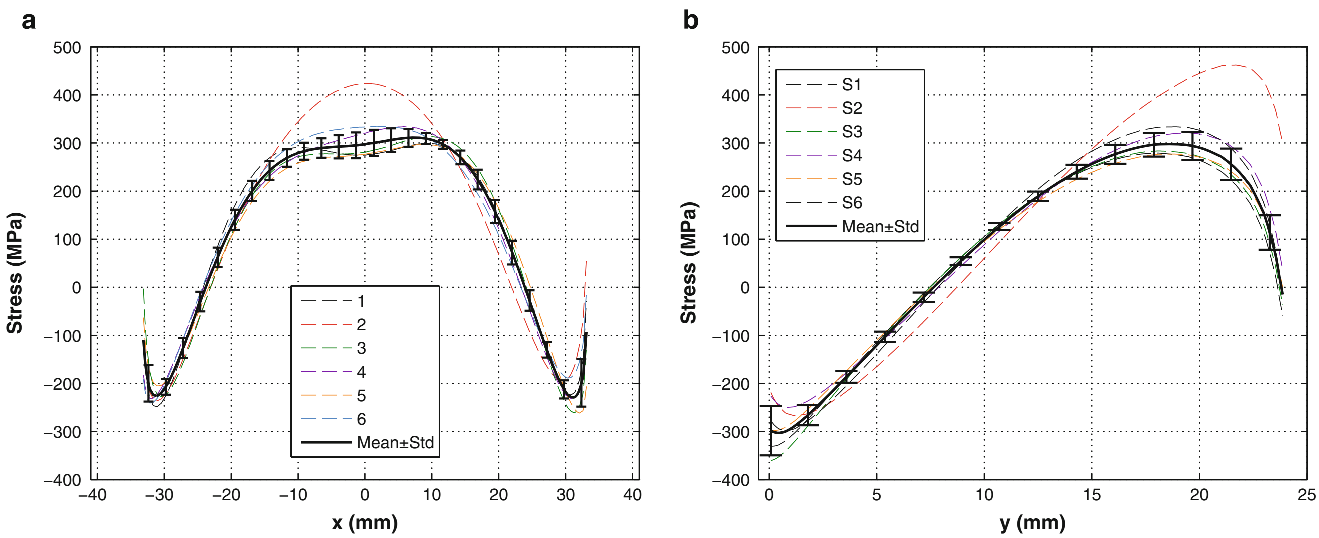

Fig. 16.14 *Line* plots of individual measurements (*dashed*) and the mean and repeatability standard (*solid black*) for the stainless steel forging samples along the (**a**) x-direction at y = 19.05 mm and (**b**) along the y-direction at x = 0

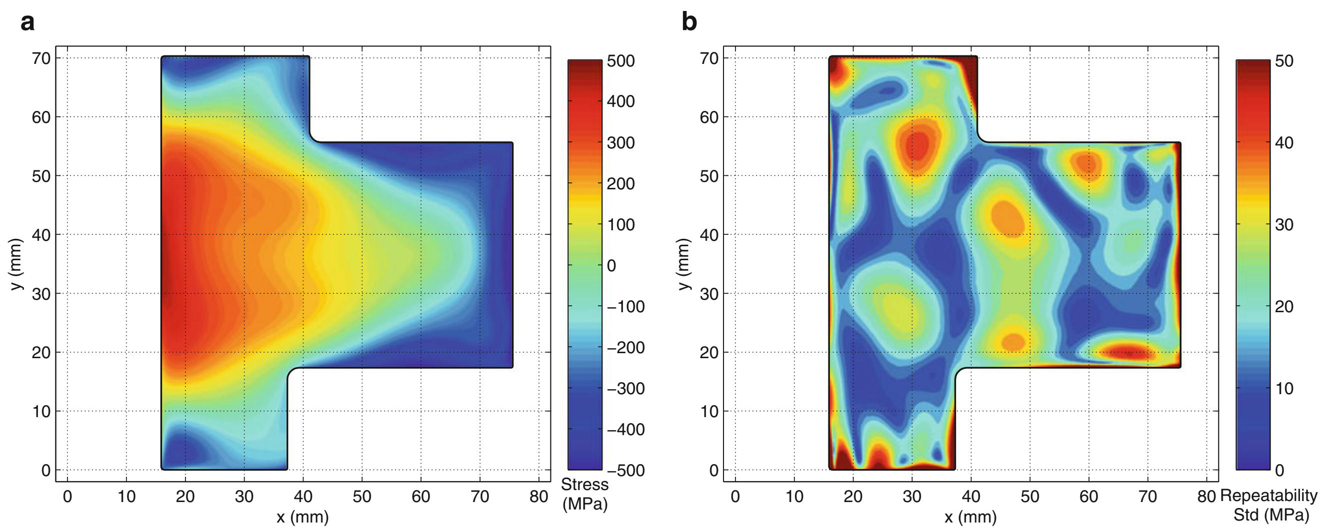

Fig. 16.15 (**a**) Mean and (**b**) repeatability standard deviation for the nickel disk specimens

Table 16.2 Repeatability standard deviation statistical values

Specimen	Median (MPa)	Mean (MPa)	75th percentile (MPa)	95th percentile (MPa)
Aluminum T-section (7085-T74)	3.7	5.1	6.2	12.6
Titanium EB welded plate (Ti-6Al-4V)	5.9	7.7	8.3	17.3
Nickel disk (Udimet-720Li)	21.5	24.9	29.7	51.7
Stainless steel forging (304 L)	20.3	23.8	27.6	52.3
Stainless steel DM welded plate	14.9	17.3	21.6	36.3

each specimen was calculated and is shown in Fig. 16.17. The median is lower than the mean, which suggests the distribution of repeatability standard deviation is skewed toward larger values. The trend is consistent across cross-sectional shapes and underlying processes (quenching, forging, welding).

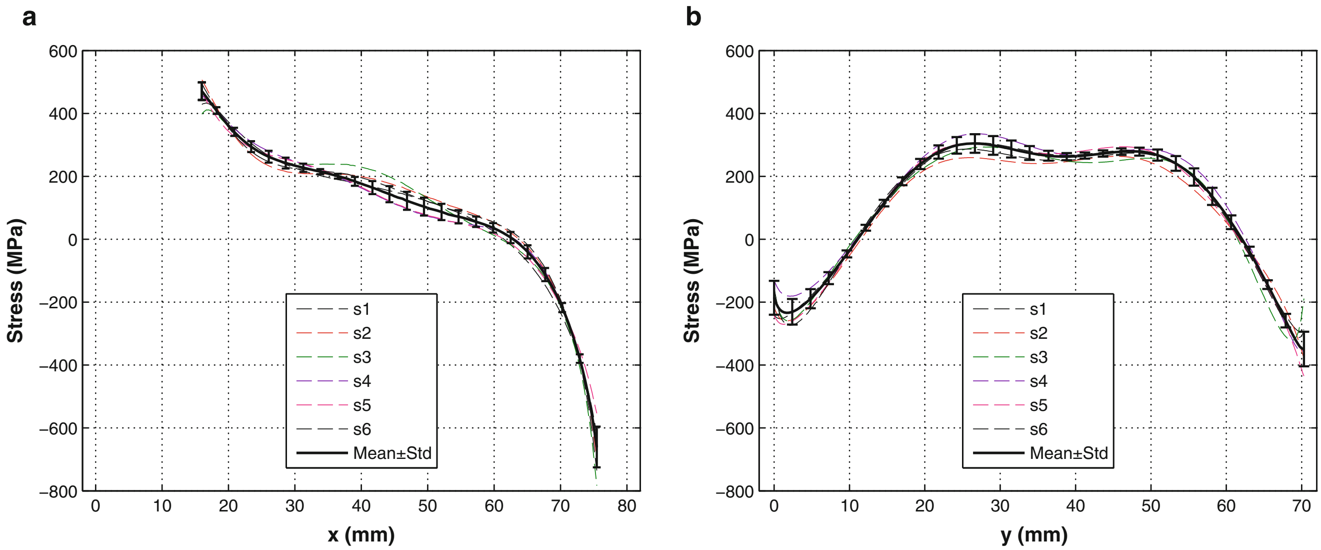

Fig. 16.16 *Line* plots of individual measurements (*dashed*) and the mean and repeatability standard (*solid black*) for the nickel disk samples along the (**a**) x-direction at y = 3.18 mm and (**b**) along the y-direction at x = 40.52 mm

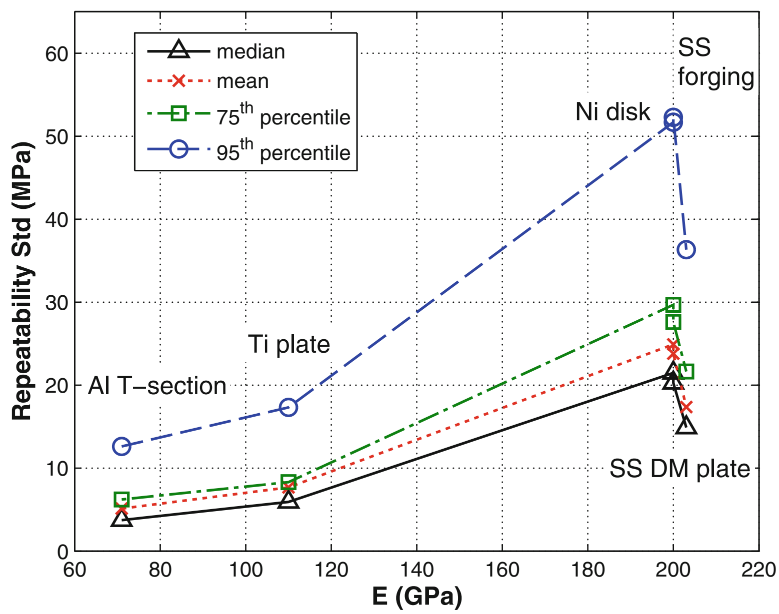

Fig. 16.17 Repeatability standard deviation versus elastic modulus (E)

16.5 Summary/Conclusions

Five repeatability studies were performed using an aluminum T-section, a stainless steel plate with a dissimilar metal slot-filled weld, a stainless steel forging, a titanium plate with an electron beam slot-filled weld, and a nickel disk forging. Each repeatability study included five to ten contour method measurements and determined the repeatability standard deviation. The results of the repeatability studies show consistent levels of repeatability over most of the specimen interior and localized regions of higher variability (typically along the part perimeter). The mean repeatability standard deviation ranged from 5 MPa for the aluminum T-section to 35 MPa for the stainless steel forging, which represent the minimum and maximum values of the population. Similarly, the value of the 95th percentile repeatability standard deviation ranged from 15 MPa for the aluminum T-section to 85 MPa for the stainless steel forging.

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