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Repeatability of the Contour Method for Residual Stress Measurement

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ABSTRACT

This paper describes the results of a residual stress measurement repeatability study using the contour method. The test specimen is an aluminum bar (cut from plate), with cross sectional dimensions of 50.8 mm x 76.2 mm (2" x 3") with a length of 609.6 mm (24"). There are two bars, one bar with high residual stresses and one bar with low residual stresses. The high residual stress configuration (±150 MPa) is in a quenched and over-aged condition (Al 7050-T74) and the low residual stress configuration (±20 MPa) is stress relieved by stretching (Al 7050-T7451). Five contour measurements were performed on each aluminum bar at the mid-length of successively smaller pieces. Typical contour method procedures are employed with careful clamping of the specimen, wire electric discharge machining (EDM) for the cut, laser surface profiling of the cut faces, surface profile fitting, and linear elastic stress analysis. The measurement results provide repeatability data for the contour method, and the difference in repeatability when measuring high or low magnitude stresses. The results show similar repeatability standard deviation for both samples, being less than 10 MPa over most of the cross section and somewhat larger, around 20 MPa, near the cross section edges. A comparison with published repeatability data for other residual stress measurement techniques (x-ray diffraction, incremental hole drilling, and slitting) shows that the contour method has a level of repeatability that is similar to, or better than, other techniques.

Keywords: Residual stress, repeatability, uncertainty, contour method, aluminum

1. INTRODUCTION

Residual stresses exist in a component in the absence of external load, and while there is no obvious evidence of their existence, they have potentially significant effects on part performance [1, 2]. There are many options for residual stress measurement, each with advantages and limitations [3]. Thus, when choosing a residual stress measurement technique, it is important to understand first what the measurement should provide (e.g., what components of the stress tensor, over how many spatial dimensions), and secondly, the required precision expected from the measurement. While the contour method has recently emerged as a useful technique for measuring residual stress [4], there is currently no published information on its precision. This study develops data to quantify the repeatability of the contour method.

Repeatability is the precision provided by a measurement technique under repeatability conditions and is generally quantified by the *repeatability standard deviation*. The repeatability standard deviation is the standard deviation of a given measurand obtained under repeatability conditions [5], where repeatability conditions are defined as the conditions where independent test results are obtained with the same method on identical test items, in the same laboratory, by the same operator, using the same equipment, in short intervals of time. Since this paper regards a destructive residual stress measurement method, it should be noted that identical test items cannot be used, so multiple measurements are made on the same article, where the measurements are expected to be nearly identical. Also of interest is the *repeatability limit*, defined as an expected maximum absolute difference between two individual test results obtained under repeatability conditions, with a probability of approximately 95%. Practically, the repeatability limit is 2.77 times the repeatability standard deviation [5]. Both the repeatability standard deviation and repeatability limit will be reported later.

Measurements are made in two long aluminum bars of rectangular cross section, one bar that contains residual stress from quenching and a second bar that is stress relieved by stretching. A carefully processed long bar is well suited to assess repeatability of the contour method because, except near its ends, the bar is expected to have the same stress field at all planes along the length. The rectangular cross section eases several practicalities associated with the contour method, including issues arising from the "bulge error", described in [6], that are mitigated with good clamping on the flat edges of the bar. A second practicality made easier in a long bar relates to cutting artifacts that can arise during cutting with a wire electric discharge machine (EDM) when cutting through a change in part thickness; this issue is mitigated by cutting across the width of a bar of uniform thickness. Thus, this specimen provides a good environment to study the repeatability of the contour method under best-case conditions. As with any repeatability study, the data developed to not address the accuracy of the technique.

2. METHODS

Measurements were done on two aluminum bars that were cut from 50.8 mm (2 in) thick rolled 7050 aluminum plate. The original plate was long, and in the T7451 condition, being over-aged and stress relieved by stretching. One bar, referred to as the stress relieved bar, had no additional heat treatment; the second bar, referred to as the quenched bar, had an additional heat treatment performed to introduce a higher stress. The quenched bar heat treatment was representative of that used for the T74 temper [7], and consisted of solution heat treatment at 477 °C for 3 hours, immersion quenching in room temperature water with 16% polyalkylene glycol (Aqua-Quench 260), and a dual artificial age at 121 °C for 8 hours then 177 °C for 8 hours. The bar cross section of both bars is 50.8 mm (2 in) thick, by 76.2 mm (3 in) wide and has an approximate yield strength of 490 MPa. The length of the stress relived bar is 610 mm (24 in) and the length of the quenched bar is 914 mm (36 in), the latter being cut to 610 mm before making measurements, as described below (**Fig. 1**). Material orientation was different in the two bars, with the rolling direction (L) along the 76.2 mm width of the quenched bar and along the 610 mm length of the stress relieved bar. We adopt a coordinate system for residual stress measurement having an origin at the bottom left hand side of the bar cross section, with positive x along the 76.2 mm width, to the right, and positive y along the 50.8 mm thickness, upward.

Contour measurements, which involve cutting the sample through a given measurement plane, were performed at five locations along the length of the bar (**Fig. 1**) The first contour measurement was at the center of the bar length (plane 1), followed by contour measurements at the center of the remaining half bars (planes 2A, 2B), followed by two contour measurements at the center of two of the quarter bars (planes 3A, 3B). In general, anytime a specimen is cut, the stress in the body is altered, with the change being large at points close to the cut and negligible far from the cut. Therefore, it is generally important to account for the effects of a cut on subsequent stress measurements [8]. In the present study, the original bar has length L that is long compared to the width and thickness, and the measurements are far enough apart so that the contour cuts are not expected to significantly alter the stress at the locations of subsequent measurements. Preliminary finite element modeling suggests that if additional cuts were performed, stress measured in the smallest remaining piece, having length $L/8$ before cutting, would be about 0.6% smaller than measured in the pieces with initial lengths L, $L/2$, and $L/4$.

To reduce end effects from quenching and accommodate the size limitation of our EDM, 152 mm (6 in) was removed from each end of the quenched bar (**Fig. 2**, planes 0A, 0B) before making contour measurements. Prior to cutting, four biaxial strain gages were attached to the top of the bar at the two contour planes closest to the end planes, with two gages on each plane, as shown in **Fig. 2**. The strain gage measurements were used to determine whether the end cuts would affect measurements at these planes. Any change of stress in the interior of the bar must be accompanied by change of stress at the surface, because the stress states before and after cutting are in equilibrium, so surface measurements are sufficient for this purpose. The strain (resistance) of the biaxial strain gages was recorded using a Wheatstone bridge strain indicator before and after end removal. Change of stress along the length, computed from change of strains using plane stress Hooke's law, was 4.46 MPa. The strain change measurements for end cutting included disconnection and reconnection of the strain gage leads, which is known to introduce uncertainty. To quantify that uncertainty prior to measurements, we repeatedly connected, disconnected, and reconnected the strain gage leads, while the gaged part was undisturbed at constant temperature. The standard deviation of these strain readings was 10 με. When that standard deviation is assumed to be the uncertainty in strain, and propagated through Hooke's law, the uncertainty of the stress release calculation is ±3.1 MPa (95% confidence interval). Given the significant uncertainty, we expect the change of stress due to end cuts was negligible, but quantitative evaluation of this effect was performed following stress measurements, and is discussed below.

Detailed theoretical background for the contour method was provided earlier by Prime [4]. Detailed experimental steps for the contour method have been provided by DeWald and Hill [9], with a brief summary given here. At each contour plane, the specimen was cut in two using wire EDM. Cutting was performed with the specimen 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. For all measurements, surface height data was taken on a grid of points with spacing of 200 μm x 200 μm, so that there were roughly 96,000 data points for each surface. The two surface profiles were then averaged on a common grid, and the average was fit to a smooth bivariate Fourier series [10]. A level of smoothing is determined by choosing fitting orders during data reduction.

The residual stress on the contour plane was found with a linear elastic finite element analysis that applied the negative of the smoothed surface profile as a set of boundary conditions on the cut plane. The finite element mesh used eight-node, linear displacement brick elements with node spacing of 1 mm on the cut face, along both x and y, and node spacing normal to the cut face that increased with distance away from the cut, being 1 mm at the cut face and 5 mm at the end of the bar. The mesh was sufficiently refined such that when the node spacing is halved there is negligible change in stress. The model used an elastic modulus of 71.0 GPa and a Poisson's ratio of 0.33 [11].

The average, repeatability standard deviation, and repeatability limit, were found for each measurement as a function of in-plane position. The repeatability standard deviation was calculated as

$$s(x,y) = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(\sigma_i(x,y) - \bar{\sigma_i}(x,y)\right)^2} \tag{1}$$

where, $s(x, y)$ is the repeatability standard deviation at a given in-plane position (x, y), N is the number of measurements (5), $\sigma_i(x, y)$ is the measured stress at (x, y) in the i^{th} measurement, and $\bar{\sigma}(x, y)$ is the mean measured stress at (x, y) [12].

3. RESULTS

Measured residual stress for the stress relieved bar can be seen in **Fig. 3**, and used a fitting orders $k_x = 1$ and $k_y = 2$ (15 terms in the bivariate Fourier series). The results show low magnitude residual stresses around ±20 MPa. The stress has a banded structure with tensile stress at the top, bottom, and center of the bar with compressive regions between; a similar banded residual stress field was seen in earlier measurements of residual stress in 7050-T7451 stress relieved plate [13]. Results for all planes are somewhat asymmetric about the mid-width (x = 38.1 mm), with the right hand side showing larger magnitude residual stress. This asymmetry is not expected in rolled aluminum plate, and may be a result of cutting irregularities, as the cutting direction for all measurements proceeded along the +x direction (left to right in **Fig. 3**). Results for planes 1, 2A, and 2B are nearly symmetric about the mid-thickness (y = 25.4 mm) but results for planes 3A and 3B have unexpected asymmetry about the mid-thickness, with the top having somewhat higher magnitude stress. This asymmetry is also unexpected, as plate rolling, quenching, and stretching are typically symmetric processes.

The mean and repeatability standard deviation for the stress relieved bar can be seen in **Fig. 4**. The repeatability standard deviation is small in the interior, under 5 MPa, and somewhat larger within about 2 mm of the upper and lower boundaries of the contour plane, reaching a maximum of 14 MPa at the left side of the upper edge. The repeatability limit is proportional to the repeatability standard deviation, and therefore follows the trends seen in **Fig. 4b**, being less than 14 MPa in the interior and being larger near the upper and lower edges and having a maximum of 39 MPa. The absolute maximum deviation of stress from the mean is 16 MPa, which occurs at the same location as the maximum standard deviation.

Line plots of the stress along two orthogonal lines for the stress relieved bar, one horizontal along x at y = 25.4 mm and one vertical along y at x = 38.1 mm) can be seen in **Fig. 5**. The mean stress shows the banded or W profile along the vertical, which was discussed above. Error bars show the repeatability standard deviation, which is a relatively large percentage of the measured stress (around 30% of the stress range). The line plots underscore the difference between most measurements and a single outlier, plane 2B, that has a larger residual stress magnitude; this outlier significantly affects the standard deviation.

The stress results for the quenched bar can be seen in **Fig. 6**, and used a fitting orders $k_x = 1$ and $k_y = 1$ (9 terms). The results show much larger residual stresses than for the stress relieved bar, with magnitudes of about 150 MPa. The shape of the stress distribution is roughly paraboloid, with tensile stress at the center of the bar and compressive stress at the outside. These features agree with previous measurements of stress in quenched aluminum bar performed by Robinson, et al. [14, 15].

The stress measurements appear to be nominally consistent, with results for plane 1 deviating from the other measurements to some degree.

The mean and repeatability standard deviation for the quenched bar can be seen in **Fig. 7**. The repeatability standard deviation is small in the interior, around 5 to 10 MPa, and somewhat larger within 5 mm of the edges, having a maximum of 20 MPa at the upper left corner. The repeatability limit follows the same trend seen in the repeatability standard deviation (**Fig. 7b**), being 14 to 28 MPa in the interior with a maximum of 55 MPa. The absolute maximum deviation of stress from the mean is 31 MPa in the quenched bar, which occurs at the edges of the 76.2 mm width.

Line plots of stress along two orthogonal lines through the sample center can be seen in **Fig. 8** for the quenched bar. The mean stress shows the paraboloid profile. Error bars show repeatability standard deviation, which is a small fraction of the stress (maximum around 5% of the stress range). Results for plane 1 are a slight outlier.

4. DISCUSSION

The repeatability data for the two measurement sets suggest a similar level of precision for measurements in the stress relieved and quenched bars. This indicates that the repeatability of the contour method may remain constant over the range of stress magnitude addressed in this study. When measuring low magnitude residual stresses, as in the stress relieved bar, the repeatability standard deviation is large relative to the resulting stress. This may or may not be acceptable, but there is not likely to be a more precise alternative for two-dimensional mapping of such residual stress fields. For high magnitude residual stresses, as in the quenched bar, the repeatability standard deviation found here is small relative to the stress magnitude.

As briefly mentioned in the Methods section each measurement will cause a redistribution of stress by introducing a new stress-free surface and this may have an effect on future measurements. To find the effect of this redistribution, one needs to find the effect of the stress release at the future measurement site, as has been exploited in other recent work [8, 16]. Conveniently, this stress redistribution is measured during the analysis step for the contour method, so one can extract the stress at the future measurement plane from the finite element model used to compute residual stress for the contour method.

The results here depend on using a stress-free cut correction, suggested earlier by Prime [4], to account for variation of the EDM cut from an ideal flat plane. This was accomplished by removing a 1.27 mm slice from the end of the block. Because the cut was adjacent to a stress-free surface, the surface profile on the cut face is assumed a result of the EDM cutting process and not stress release. The cut profile on the face of the larger piece, called the stress-free profile, was measured using the same procedure as used during the contour experiments. The measured stress-free profile was then subtracted from the profile measured during each contour measurement to correct for the non-flat EDM cut. The differences due to the stress-free cut correction are nearly negligible in the quenched bar, but large in the stress relieved bar, with differences in residual stress less than 20 MPa for both bars. The contour results for the stress relieved bar at plane 3A without the stress-free cut correction in **Fig. 9a** can be compared with the corrected results in **Fig. 3d**, and the comparison shown as a line plot in **Fig. 9b** show the significant effect for the stress relieved bar.

Previous studies of residual stress measurement repeatability give useful context to the results presented above. Published repeatability studies were available for x-ray diffraction, incremental hole drilling, and slitting.

An x-ray diffraction repeatability study by Fry [17] made x-ray diffraction measurements for three different materials (a shot peened CCr3 spring steel block, a quenched 7010 aluminum block, and a ground piece of titanium alloy) using a tabletop x-ray diffractometer to assess the instrument-operator repeatability. In each case, ten repeat measurements were conducted, where the specimen was removed and replaced in the x-ray diffractometer between each measurement. In this manner, the standard deviation of the measurement sets was established to be 8 MPa for the spring steel block, 3 MPa for the quenched 7010 aluminum block, and 18 MPa for the ground piece of aluminum. The good repeatability is consistent with the minimal interaction between the test equipment and the test specimen in these measurements; one should expect significantly larger repeatability bounds when performing stress versus depth profiling using x-ray diffraction with layer removal on account of the greater interaction with the sample.

The study by Lee and Hill [18] made five measurements of residual stress versus depth from the surface using the slitting method in thick blocks removed from a single plate of 316L stainless steel. The plate had been uniformly laser peened to induce a deep residual stress field after which the plate was cut into blocks. Typical slitting method techniques were employed with a single back face strain gage and incremental cutting by wire EDM. Residual stress profiles were found as a function of depth from the surface using a polynomial basis. The maximum standard deviation of the five measurements occurred at the surface, and was 15 MPa, but the standard deviation away from the surface was less than 7 MPa; the absolute maximum deviation also occurred at the surface, and was 26 MPa.

Three incremental hole drilling interlaboratory reproducibility exercises have been performed [19, 20]. Two studies are reported by ASTM on specimens nominally free of residual stress, where one study used stress relieved AISI 1018 carbonsteel and the other used stress relieved 304 stainless steel, and where the hole drilling data reduction procedure assumed constant residual stress as a function of depth [19]. The repeatability standard deviation in these two sets of nominally stress free specimens was 14 MPa and 12 MPa, respectively. A cautionary note [19] states that measurements on samples with non-zero residual stress should be expected to exhibit larger variability than found for unstressed samples. A second note states that additional variability should be expected when determining residual stress as a function of depth, a capability that was recently added to the ASTM standard. A third study by National Physical Laboratory (NPL) in the United Kingdom addressed reproducibility when determining residual stress as a function of depth with hole drilling. The NPL reported results for a shot peened steel sample and a friction stir welded aluminum sample. Unfortunately, there is not a direct reporting of the reproducibility standard deviation of the measurements, but rather stress versus depth for some of the participating laboratories at some cut depths. The standard deviation was not reported, but was approximated by the present authors, and ranged significantly depending on the material and underlying residual stress state, being lower for friction stir welded aluminum (about 40 MPa) and higher for shot peened steel (several hundred MPa), with data dispersion being higher near the surface and lower at 1 mm depth. There are three general cases that the repeatability studies fall into: surface measurements with little mechanical interaction with the sample (e.g., x-ray without layer removal), mechanical interaction with the sample but stress assumed constant with position (hole drilling), and mechanical interaction with the sample with spatially varying stress fields (incremental hole drilling, slitting, and contour). These classes should be expected to show increasing repeatability limits in the order listed for practical reasons. The contour method repeatability data developed here suggest that the method has good precision relative to other residual stress measurement techniques, especially considering that the measurement provides a two-dimensional map of a spatially varying stress field.

5. SUMMARY

The present work has established repeatability data for the contour method in two long aluminum bars, one containing a low level of stress, of about ±20 MPa, and the second containing a high level of stress, of about ±150 MPa. Five repeated measurements in each part show repeatability standard deviation between 5 and 10 MPa over most of the measurement plane and about 20 MPa near the plane boundaries. The repeatability results for the low and high stress bars were nearly identical even while the stress in each bar was significantly different. The level of repeatability found here is in reasonable agreement with that found in other residual stress measurement repeatability studies. However, the repeatability data were gathered in a relatively straightforward measurement configuration having a simple geometry and opportunity for secure clamping; more complicated measurement configurations may lead to increased repeatability limits.

6. ACKNOWLEDGEMENTS

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FIGURES

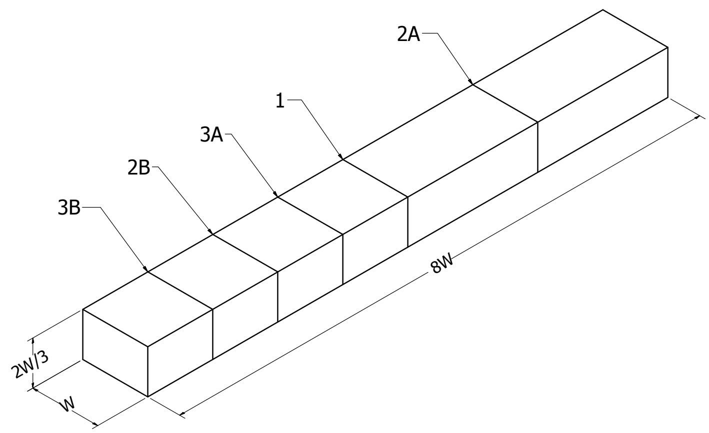

Fig. 1 *– Dimensioned aluminum bar with contour planes. Normalized dimension shown, where W=76.2 mm*

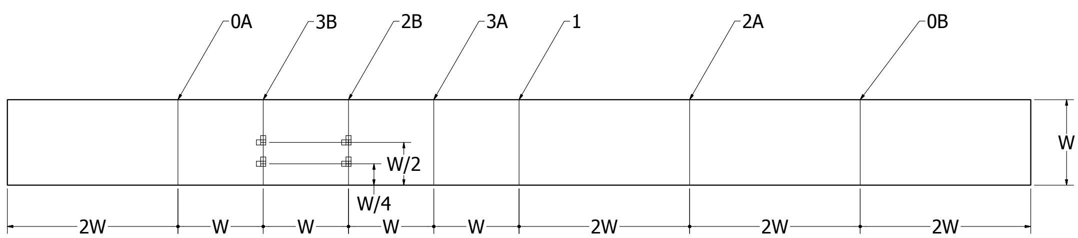

Fig. 2 *– Dimensioned aluminum bar with contour planes and locations of four biaxial strain gages used to measure strain during end removal (planes 0A and 0B) for the quenched bar. Normalized dimension shown, where W=76.2 mm*

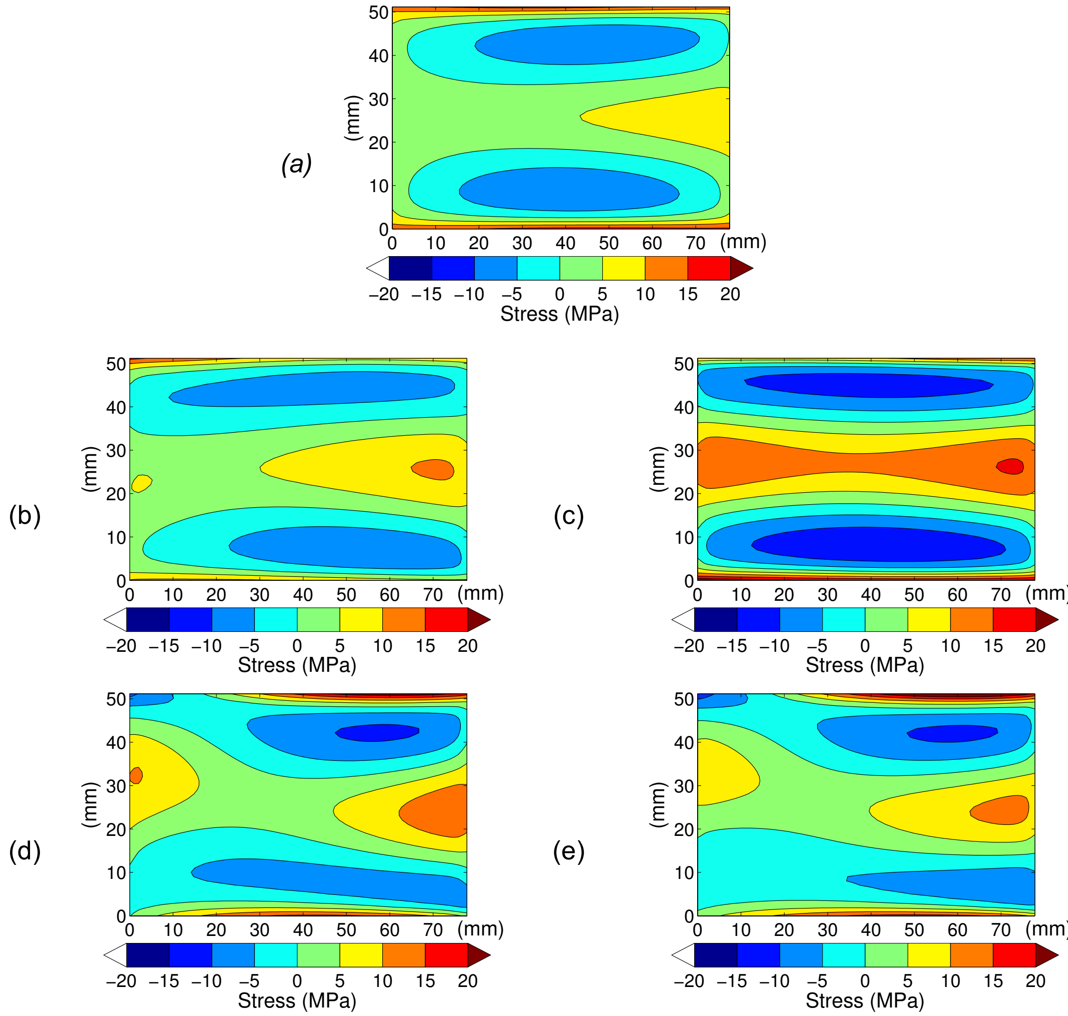

Fig. 3 *– Stress in the stress relieved bar for (a) plane 1, (b) plane 2A, (c) plane 2B, (d) plane 3A, and plane 3B*

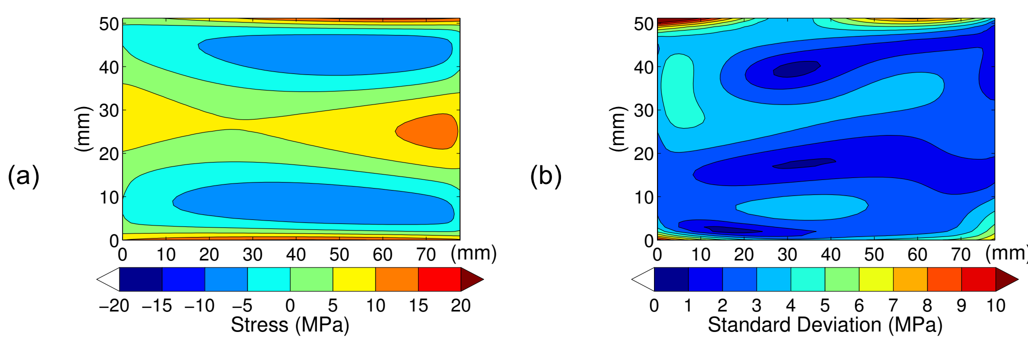

Fig. 4 *–Mean (a) and repeatability standard deviation (b) of stresses for the stress relieved bar*

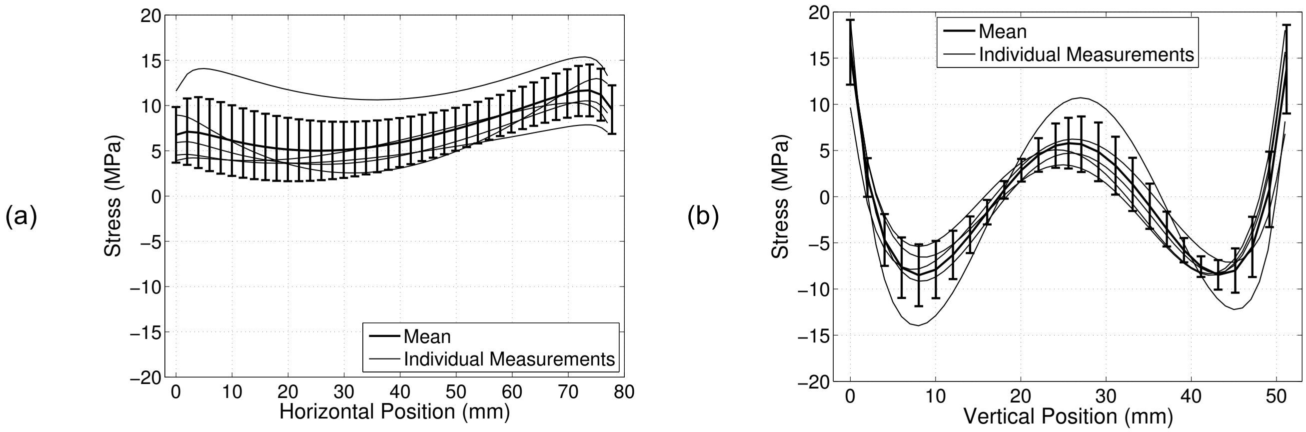

Fig. 5 *– Line plots for the stress relived bar (a) horizontal along the vertical mid-thickness and (b) vertical along the horizontal mid-thickness, where the error bars are the repeatability standard deviation. The outlier is plane 2B*

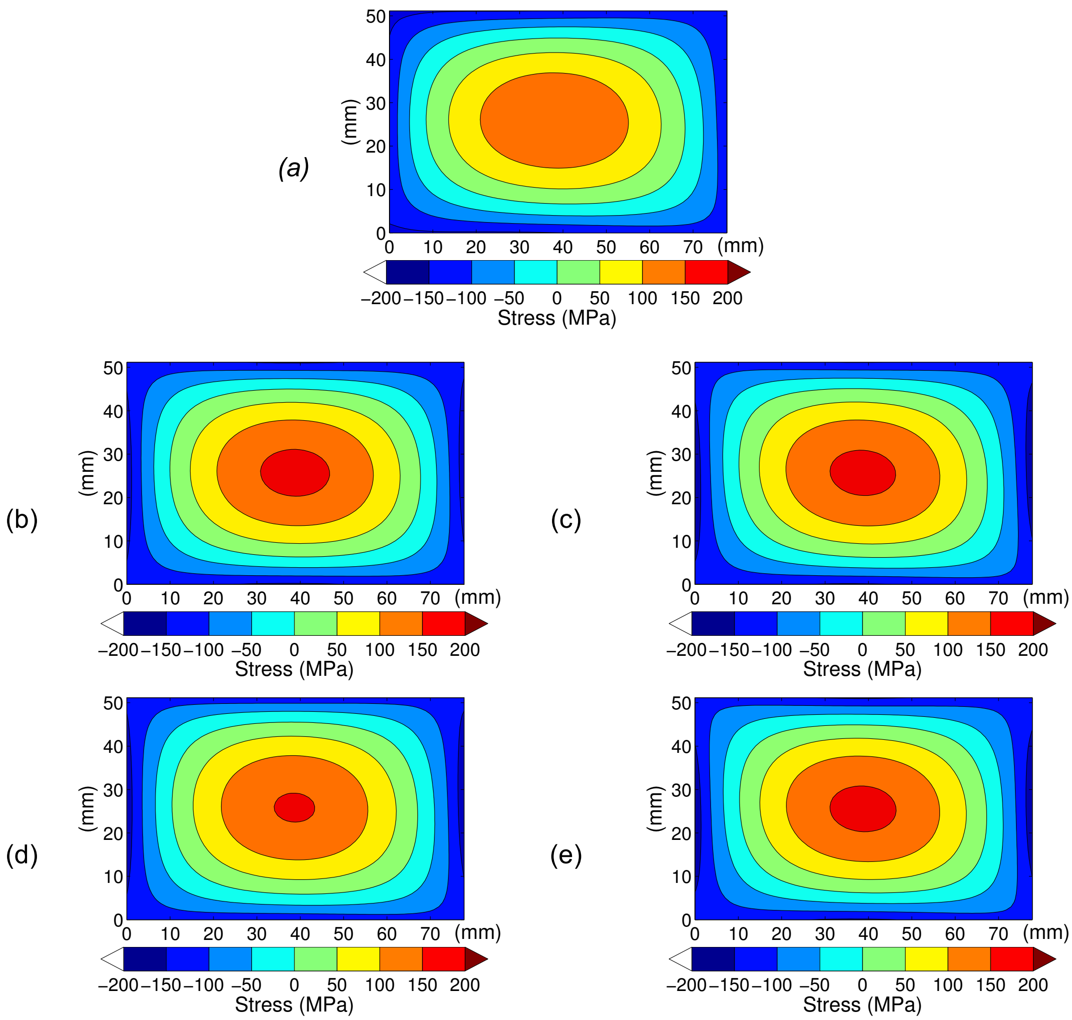

Fig. 6 *– Stress in the quenched bar for (a) plane 1, (b) plane 2A, (c) plane 2B, (d) plane 3A, and (e) plane 3B*

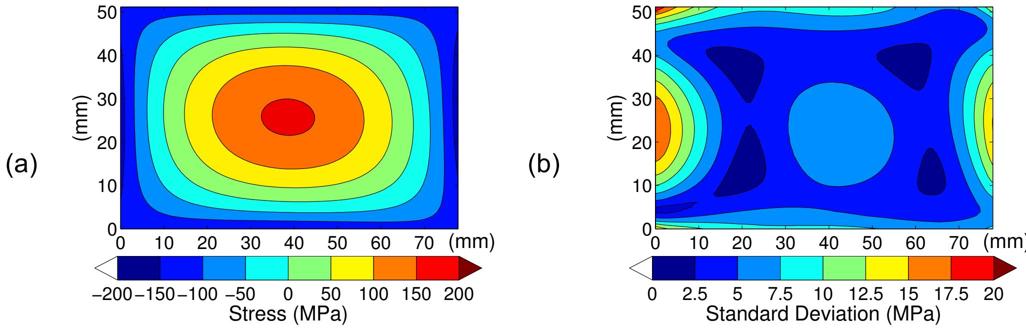

Fig. 7 –*Mean (a) and repeatability standard deviation (b) of stresses for the quenched bar*

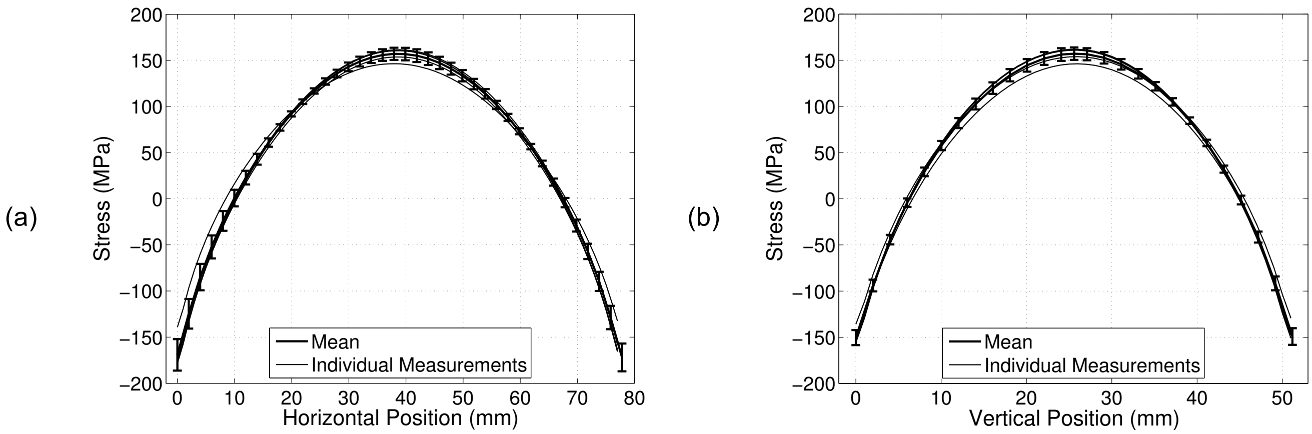

Fig. 8 *– Line plots for the quenched bar (a) horizontal along the vertical mid-thickness and (b) vertical along the horizontal mid-thickness, where the error bars are the repeatability standard deviation. The slight outlier is plane 1*

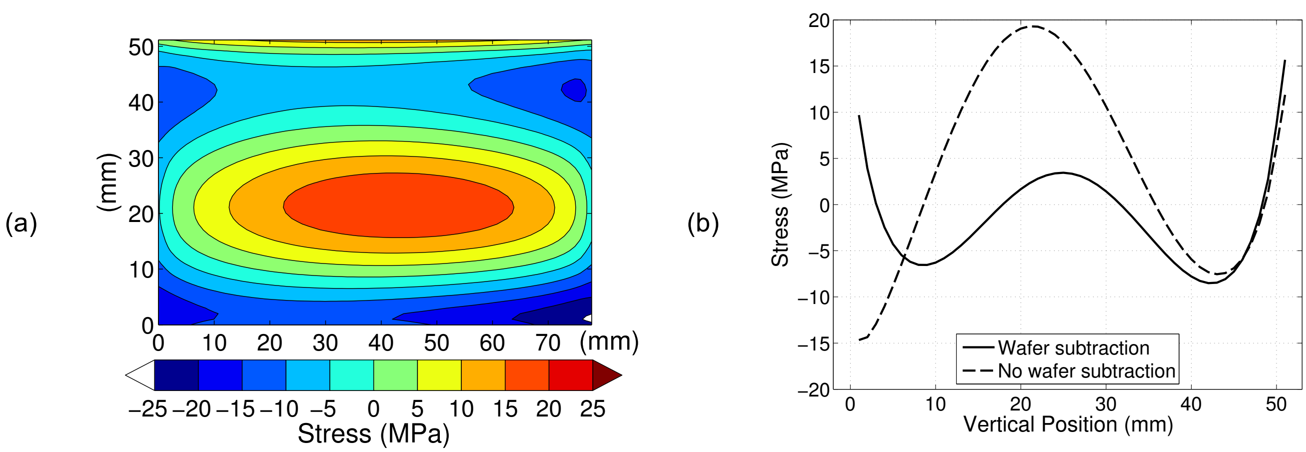

Fig. 9 *–Stress in the stress relived bar (a) without stress-free cut correction and (b) vertical line-out at the mid-width showing the stress with and without the stress-free cut correction*