Effect of Residual Stresses Embedded within Workpieces on the Distortion of Parts after Machining

Jean-François Chatelain, Jean-François Lalonde, and Antoine S. Tahan

***Abstract*—** The life of a structural part for aerospace use is usually a function of the interactions between the existing component defects, the loading conditions in service as well as the existing residual stresses within the parts. Depending on their type, distribution or magnitude, the residual stresses can be beneficial or destructive for the component. Each of the many manufacturing processes used to produce components always adds to the residual stresses, resulting in a final distribution affecting the mechanical properties and producing dimensional and geometrical distortions for the part features. These may lead to high rejection rates and quality-related problems during component assembly. This paper proposes an experimental approach to determine the influence of existing residual stresses within workpieces on the distortion of parts following machining operations. This study compares parts machined from a special 7475-T7351 aluminum alloy material exempt of residual stresses with those machined using the same alloy type but processed through standard approach leading to embedded residual stresses within the rolled material. The residual stresses were measured before and after the machining process for both material types, using the neutron scattering non-destructive inspection technique. The part deformations were evaluated using a coordinate measuring machine equipped with a laser high density scanning head. The results show that the sample parts machined from standard raw materials underwent deformations while those machined from raw materials with a controlled process underwent none or very few deformations. It was observed that the distribution, signs, and magnitudes of the residual stresses may be at the origin of the deformations measured, which indicates that residual stresses embedded within the raw material are partly responsible for the distortion of the part following the machining operation.

***Keywords*—** CAD/CAM, machining, part distortion, residual stresses, thin walls

I. Introduction

THE life of a structural part for aerospace use is usually a function of the interactions between the existing component defects, the loading conditions in service as well as the existing residual stresses within the parts. Depending on their type, distribution or magnitude, the residual stresses can be beneficial or destructive for the component, with no one option guaranteed. The residual stresses may be considered as negligible or critical, depending on the particular case. Each of the many processes used in manufacturing components always adds to the residual stresses, resulting in a final distribution affecting the mechanical properties and producing dimensional and geometrical deviations for the part features.

Considering the current trend to minimize the weight and optimize the material performance of aerospace components for which severe tolerances are requested, the analysis and comprehension of residual stresses due to manufacturing processes is of crucial. In this field, problems associated with distortion may be divided into two categories [1]. The first is related to the assembly process. Distorted parts may be too stiff to be properly mated with assemblies, and in these cases, hot straightening or shimming is considered in order to correct and adjust the parts for proper assembly. These have an impact on the final aircraft weight and assembly time. The second category, where distortion has a severe impact, concerns the material properties of the component. A distorted part is pre-loaded during assembly, which reduces its capability to sustain the loads for which it is designed. This may result in a permanently deformed part after assembly, just as is the case after machining. For example, the well-known buckle phenomenon, namely “oil canning” (Fig. 1), is likely to occur for thin-walled structural aerospace parts. This wave shape distortion decreases the component strength and fatigue endurance. To prevent this phenomenon, some of the parts features must have their thickness increased, resulting in an overall increase in the aircraft weight and cost, as well as a decrease in performance. A study by Boeing, based on four aircraft program data, estimated the “rework” and “scrap” costs related to parts distortions to come in at over 290 million dollars [2]. The same study revealed that the distortion applied to thin-walled parts has a 47% chance of causing a non-conformity in dimensional or geometrical tolerances.

The main objective of this research is to study and determine the extent to which the existing residual stresses within raw material “workpieces” used for the production of structural parts is responsible for the resulting parts deformation occurring following their machining operations, and that is caused by the stress relief mechanism.

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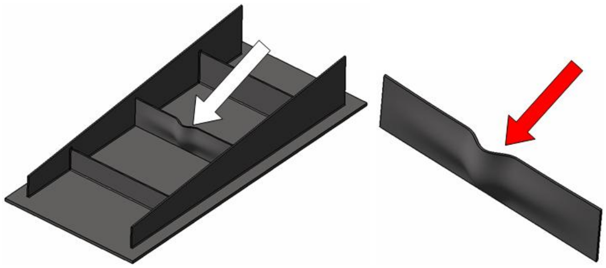

Fig. 1 Oil canning of a thin wall

The study focuses on the machining of thin-walled structural parts, which usually manifests a higher degree of distortion. The following sections present background information on the residual stresses induced by manufacturing processes. The experimental procedure, set-up, and inspection methods are explained, and the results are then presented and analyzed in the final section of the paper.

II. PART DISTORTION IN MACHINING

It is known that distortion results from the cumulative effect of several variables in a process. A survey of the literature reveals that the main variables affecting the residual stress distributions within a part that influence its final distortion are the component design, the type of material, the set-up configuration, the raw material processing and the cutting mechanism of the machining itself (Fig. 2).

A. *Part Design*

Part design and material type are two variables that may influence all the other variables. In fact, the shape of the component to be machined determines the requirements respecting set-up, raw material type and machining, which will all be responsible for induced stresses. Since the component shape is complex, it may involve many clamping configurations to prevent clamping stresses in thin- walled parts. The machining conditions, material removal rate and cutting tools selection will also depend on the component shape, where more challenging cutting strategies and parameters may be required [3]. The shape also influences the choice of manufacturing process for the raw material (casting, forging, extruding, rolling, etc.). This will lead to different stress distributions and part distortions. The last parameter related to part design is the “size-to-thickness” ratio, which expresses the wall thickness with respect to the size of the component. Generally, the distortion of machined parts is likely to happen for thin-walled components [1], [4], [5].

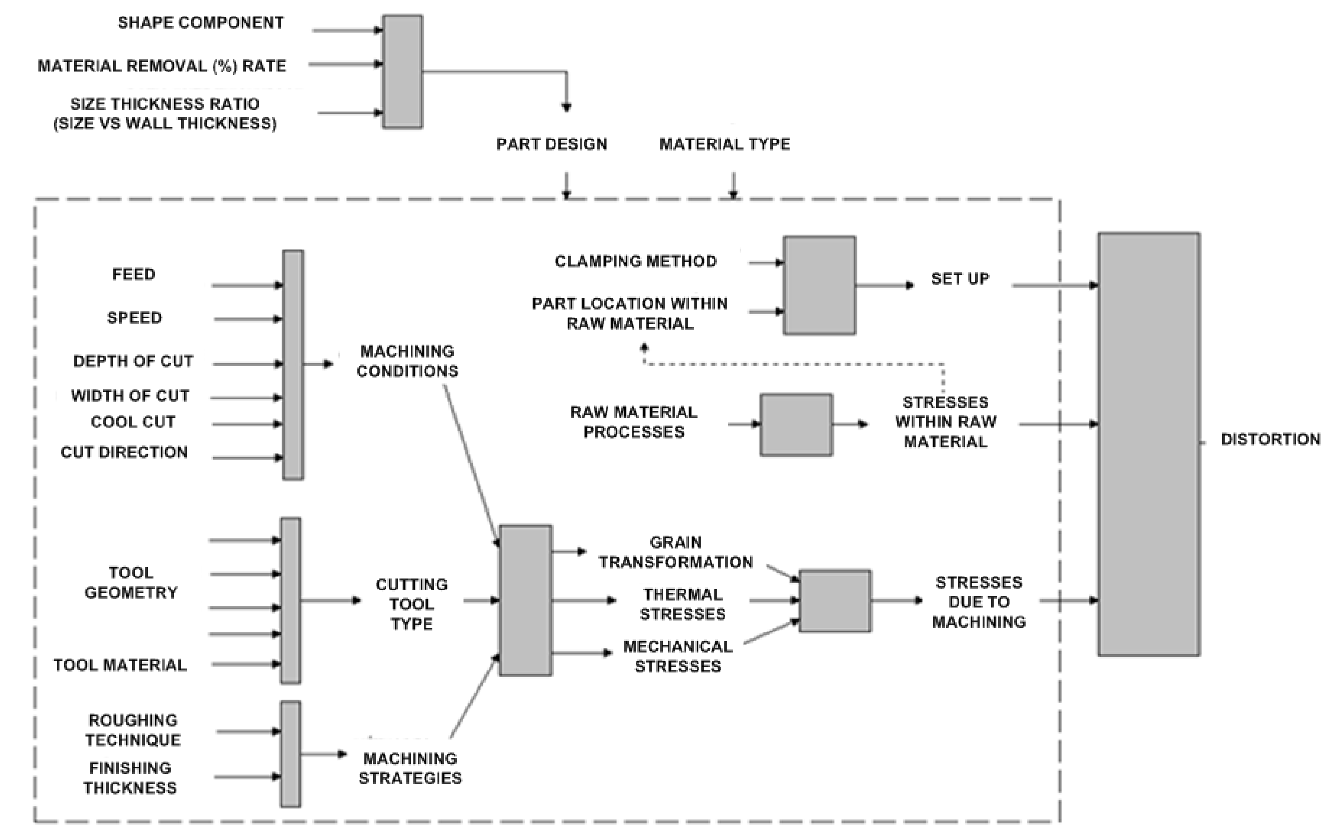

Fig. 2 Source of residual stresses related to the machining of parts

B. *Part material and setup*

The material certainly plays a primordial role, influencing all the variables interacting on the part distortion. The material type will have an effect on the set-up with respect to the grain size and orientation, the raw material manufacturing process (mechanical properties, grain size and orientation), and its machinability [6], [7]. Residual stresses due to set-up are influenced by the holding forces and location as well as from the part model location embedded within the raw material. The workpiece may be subject to tensile or compressive stresses, depending on the fixture type. A vacuum table acting on a bow workpiece will produce tensile stresses, while a part secured using a vice may induce compressive stresses. Nowag *et al.* [8] studied the effect of holding methods on part deformation, and found that they have a significant effect for the application studied.

C. *Initial stresses in raw material*

In the aerospace industry, aluminum is largely used and produced as a raw material from different manufacturing processes, e.g., forging, moulding, rolling and extruding. They are also subjected to heat treatment for improved mechanical properties. All these operations induce residual stresses within the material. A good example is the 7050-T7451 high strength aluminum plate, which is produced through successive operations, including heat treatment, quenching, artificial aging and Tx51stress relief operations. Such operations are the source of thermally-induced compressive residual stresses at part surfaces and tensile stresses in the core of thin plates [9]. A typical distribution is shown in Fig. 3. For other type of processes and aluminum, Young [1] relates that more complex profiles are observed with several successive compressive-to-tensile states through the part thickness. Several works address this problem through experimental and finite element analysis, in order to develop new processes or control methods which will reduce residual stresses in the raw material [10], [11], [12], [13].

D. *Stresses due to machining*

Another important source of residual stresses in parts is the machining process. Totten and Mackenzie [14] postulate that residual stresses result from a combination of three mechanisms: unequal plastic deformations due in part to mechanical forces, unequal plastic deformation due to thermal effects, and volume change of the material due to solid phase transformation. This last mechanism is due to the high temperature transmitted from the cutting tool to the part material during machining. The phase transformation causes an increase in grain size, which results in compressive stresses following the cooling of the material. According to the authors, such a transformation is of major concern, and in some cases, may be the dominant part distortion source. The residual stresses produced from machining may be of comparable magnitude to that produced from raw material processing. However, the distribution affects the surface rather than the core of the machined part. A typical distribution is illustrated in Fig. 4, and shows a rapid decrease in stress magnitude through the depth of the part as it goes above 0.6 mm (0.025 inch) [1].

The distribution and magnitude of the stresses through the depth is known to be a function of the machining conditions for a given material, e.g., speed, feed, depth of cut, cutting tool geometry, tool path strategies, etc. Interesting and thorough research is being pursued in this area [8], [15], [16], [17], [18]. Regarding aerospace applications, many parts having thin walls and webs as low as 0.38 mm (0.015 inch) are machined. Knowing, from X-ray measurements, that significant stresses are measured at a depth of 0.13 mm (0.005 inch), and considering the machining on both sides of a wall, this means that stresses are induced within ~66% of the material thickness [1].

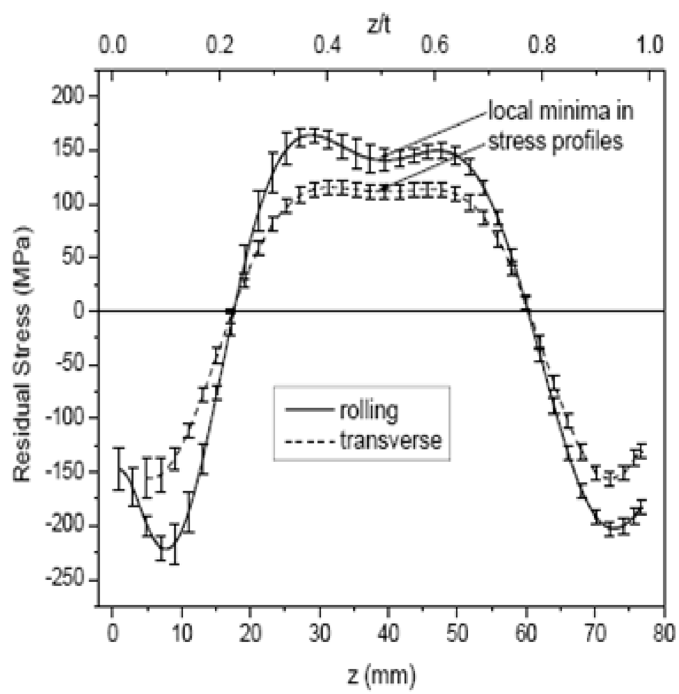

Fig. 3 Stress distributions for 7050-T74 [9]

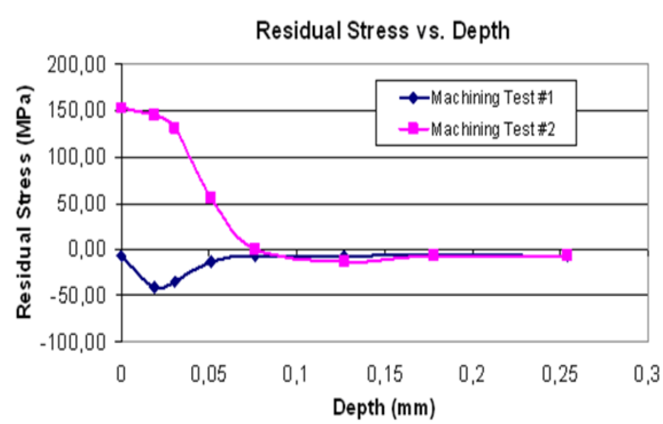

Fig. 4 Stresses induced from machining [1]

III. EXPERIMENTAL PROCEDURE

To evaluate the impact of stress relief due to machining, the same conditions were used to machine a test part from two different workpiece material types. The first type was derived from the standard processing of aluminum alloy 7475-T7351 (ISO AlZn5.5MgCu) billets, while the second is the same alloy, but processed using a special "recipe" which minimizes the residual stresses within the workpiece.

The model part to be machined was specially designed to simulate the distortion problems found on some large parts of aircraft structures following their machining operations. From preliminary tests, the cutting conditions and the set-up were selected such as to reproduce the distortion for the low-scale part model proposed (Fig. 5) in lieu of the real parts. These machining and set-up conditions were rigorously applied for all the six (6) machining tests performed (three repetitions using the two aluminum alloy raw material types). The first machining stage for this part includes a facing sequence for the bottom surface, a roughing and finishing sequence for the side and a drilling sequence which is carried out to bolt the part for the next machining stage. This second stage is performed to machine the thin wall pockets and the top surface of the part.

In this work, we will study the stress magnitude at different locations on the part as well as the final part deformation. To measure the deformation, a Coordinate Measuring Machine (CMM) equipped with a Metris LC15 laser scanning head was used to digitize the parts (accuracy of 0.055mm). The dense measurement data was then processed using the PolyWorks® software by InnovMetrics®, in order to evaluate the part deviation with respect to the nominal CAD model. To measure the residual stresses within the part, before and after the machining operations, the neutron diffraction method was selected as the most appropriate for this application. The physical approach of this method is similar to the X-ray diffraction technique, but its penetration reading capability is higher, with depths of up to 250 mm for the aluminum material [19].

This method is however time consuming, and its rareness makes it costly to use. Typically, it takes a few minutes to measure the stress at a single point location within the material. Since several parts are needed to be measured for comparison, and considering the time frame availability of the equipment, a measurement pattern is proposed in Fig. 6 to limit the number of inspections, but to have a significant representation of the stresses, considering the symmetry of the part. In fact, the symmetry along the Y-axis has been confirmed through preliminary tests, leaving the inspection process to one half for each part. The number of inspection points and their locations within the parts was determined with regards to the part design, where lines of points are located within the thin walls and the bottom of the part model (Fig.6). The lines of points are labeled X1 to X6, Y1 to Y5, Z1 and Z2, where X, Y and Z are respectively the normal, longitudinal and transverse directions of the workpiece. The uncertainty of the method is estimated at 14.7 MPa and no repeatability of the measurements was done due to time limitation.

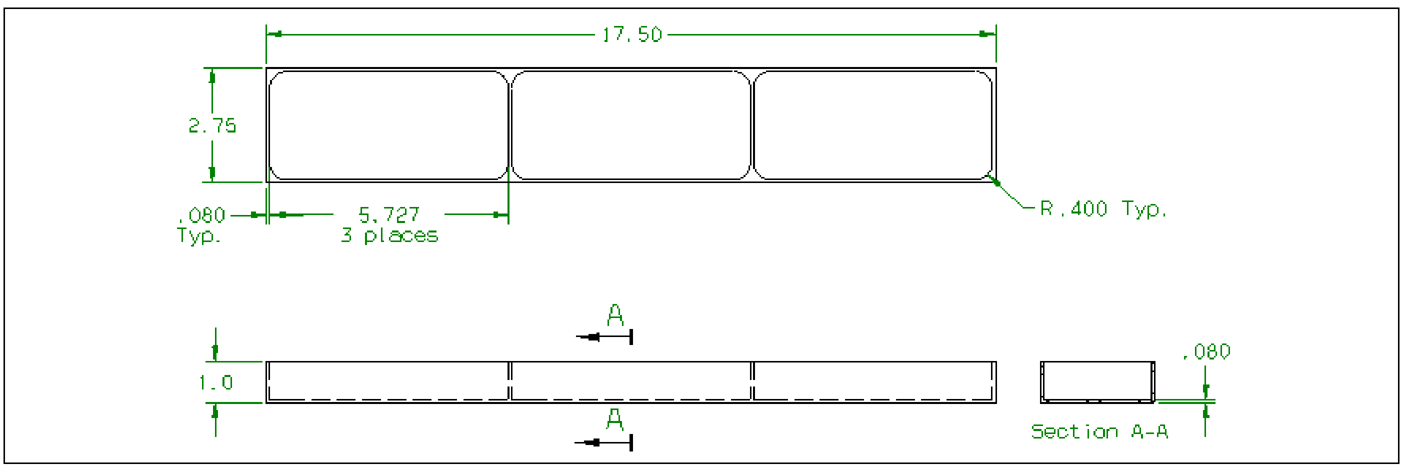

Fig. 5 Part model specifications (dimensions are in inches)

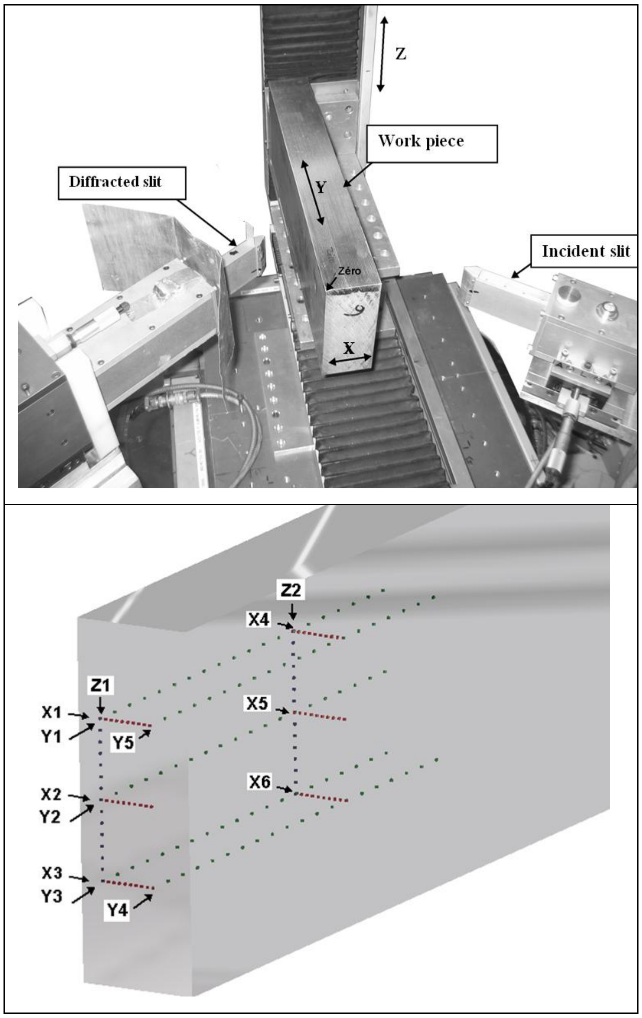

Fig. 6 Location of the stress measurements using the Neutron diffraction method

IV. Results

From the measurement of the standard and controlled material along each direction, a strong similarity in the stress distribution is observed for each of the three parts belonging to the same group, both for the standard and the controlled material. These similarities are observed for all directions. Regarding the stress magnitudes, a ± 60 MPa variation is measured for the standard material against a ± 20 MPa for the controlled material in the normal direction. Again, a ± 20 MPa variation against a ± 10 MPa variation is measured for the longitudinal direction, and a + 60 to - 20 MPa variation against a + 30 to - 20 MPa variation is observed for the transverse direction. The stress magnitude is significantly lower and more uniform for the controlled material. Due to symmetry of residual stresses distribution and part design, we found equivalent magnitudes for the Y1, Y2 and Y3 measurement lines set as well as for the Y4 and Y5 set. Therefore, only the measures of Y1 (base of the part) compared to the Y5 (top of pockets) points are plotted in Fig. 7 to show the difference in magnitude and direction of the stresses for the material before machining. Plots for parts #1 to #3 are related to the standard material (Fig. 7a), while plots for parts #5 to #6 are related to the controlled material (Fig. 7b).

The stresses specifically related to the part distortion were mainly found in the longitudinal direction (bending toward the base or toward the top of the part around the Z axis) [20]. It is known that the contribution of both the X-axis and Y-axis components of the stress relate to the longitudinal bending. Based on this, and for clarity of comparison between the Y1 and Y5 measurements, a focus on the normal stress component, is presented in Fig. 8, which is an enlargement of Fig.7 showing the normal curves only. This is to appreciate the difference in magnitude and direction of stresses along the Y1 line against those along the Y5 line of measurement. Very similar comparison was observed for the rolling component, as presented in Lalonde [20].

The plots for the standard material show that all parts have a low tensile stress in their base and a significant compression stress at their top of pockets (Fig. 8). The part with the controlled material has a different distribution, with lower magnitudes and opposite directions of stresses, with a compression at the base and tensile at the top within a ± 20 MPa interval, which boils down to be a quasi-equilibrium state for part #4. Part #6 has a similar distribution, but with slightly higher compressive stresses for the base of the part. As opposed to these two, part #5 demonstrates high tensile stresses at the top of the part.

The measured deflection for all parts, as shown in Fig. 9, seems to be directly related to the stress pattern measured. The magnitude of the deflections with respect to the nominal model varies from -1.0 mm to +0.3 mm of error. The reference for measurement is located at one end of the part (where 0 mm of deviation is found for all parts). The results show a difference in the part distortion, which depends on the initial condition of the aluminum alloy used. All three parts machined with the standard material suffer important deformations up to 1mm, while the parts machined using the controlled material have distortions at as little as 0.134 mm. In fact, the three components machined from standard aluminum have maximum deviations of -0.806mm, -0.827mm and -1.010 mm, respectively. Part #4, having almost identical stresses for the base and top sides, has a maximum deviation of -0.134 mm, while parts #5 and #6 have a maximum deviation of +0.306 mm and -0.311 mm, respectively. The positive stress for part #5 indicates a distortion in the direction of the base of the part, while the negative direction indicates a distortion in the direction of the pockets. The magnitude of tensile stresses at top of this latter part compared to the compressive state at the bottom is in concordance with the positive distortion result. For part #6, it is difficult to relate the negative deformation with the resulting stresses from the curves. The Neutron scattering system measurement uncertainty may explain this discrepancy.

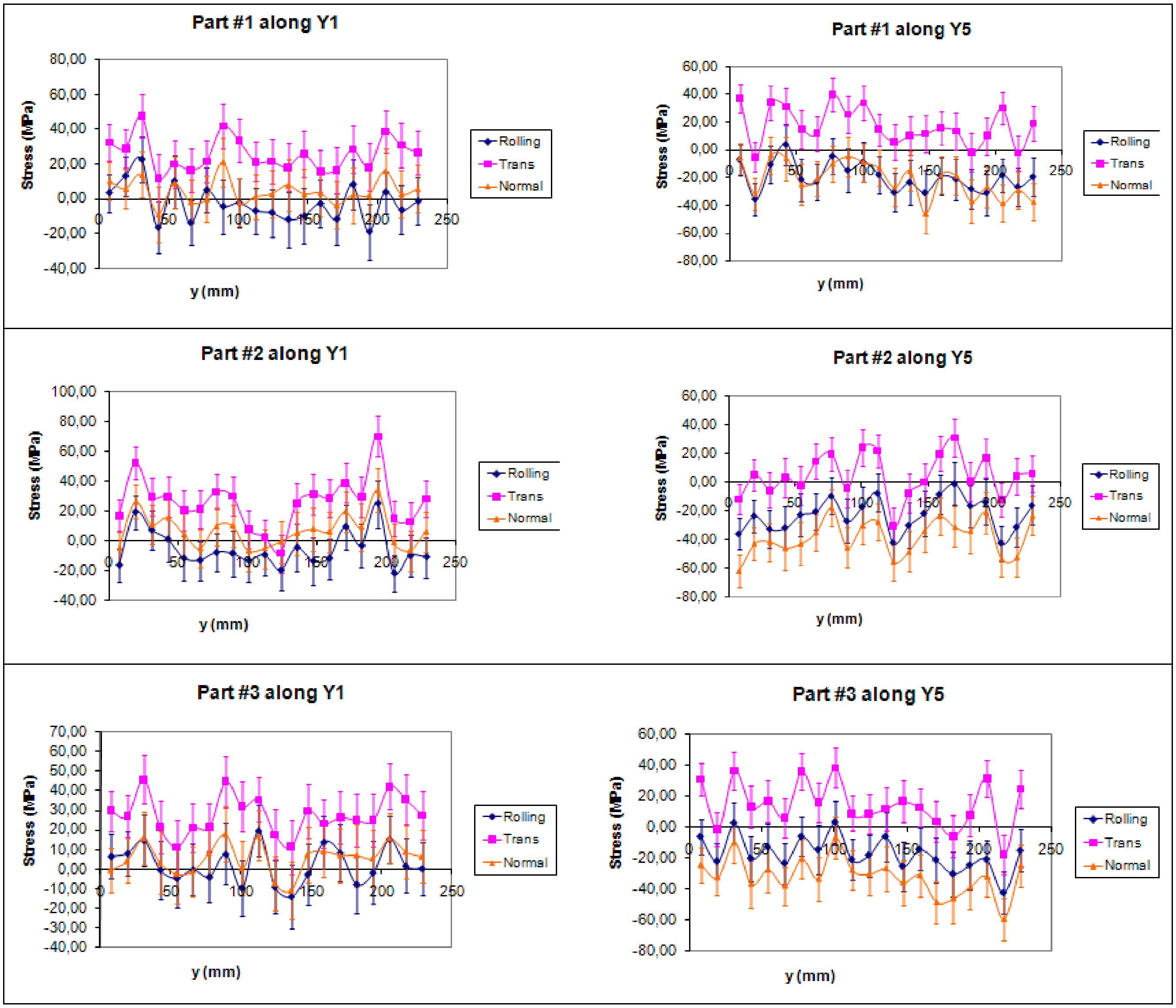

Fig. 7a Rolling, transverse and normal components of residual stress for standard material (parts #1, #2, #3)

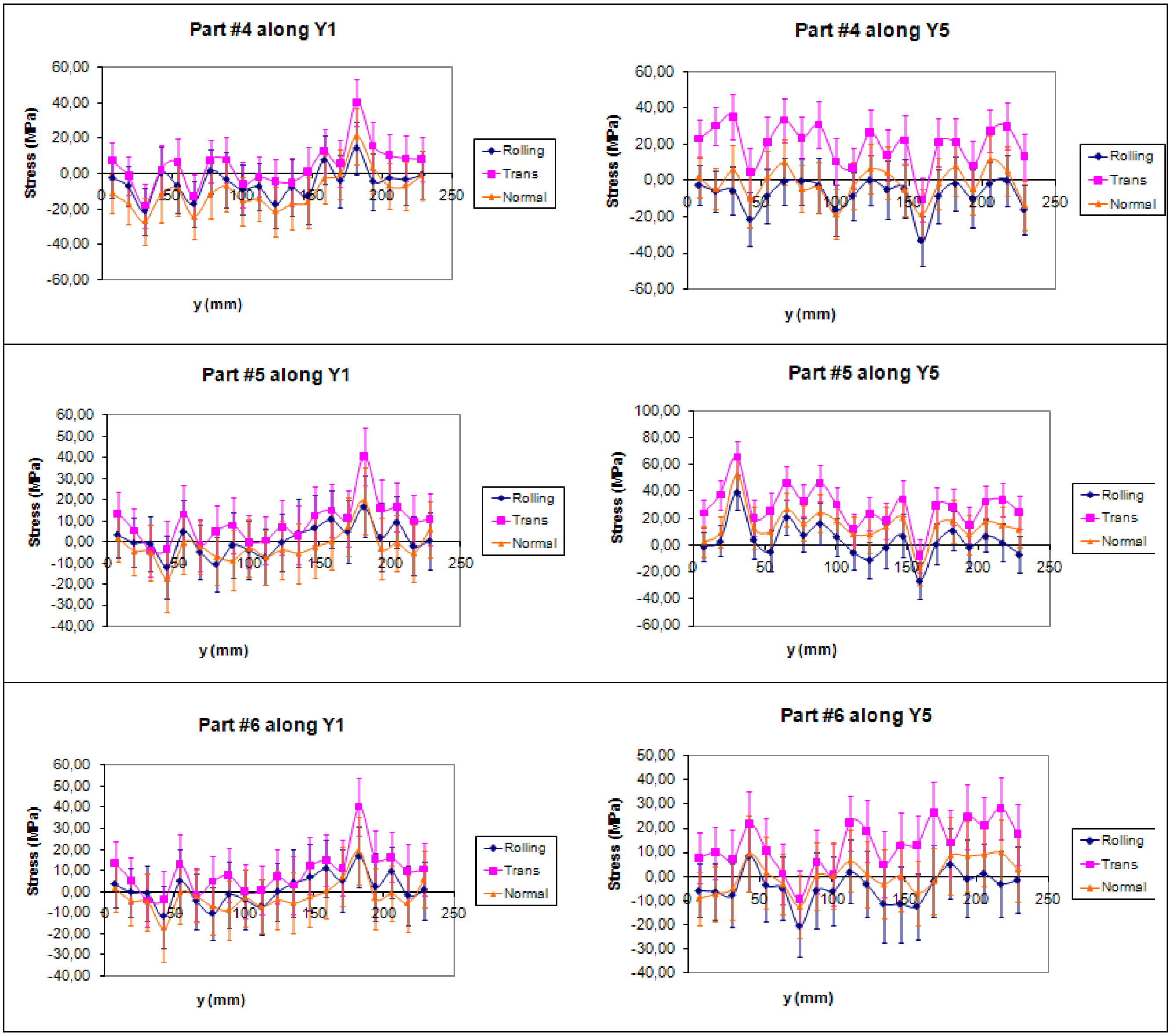

Fig. 7b Rolling, transverse and normal components of residual stress for controlled material (parts #4, #5, #6)

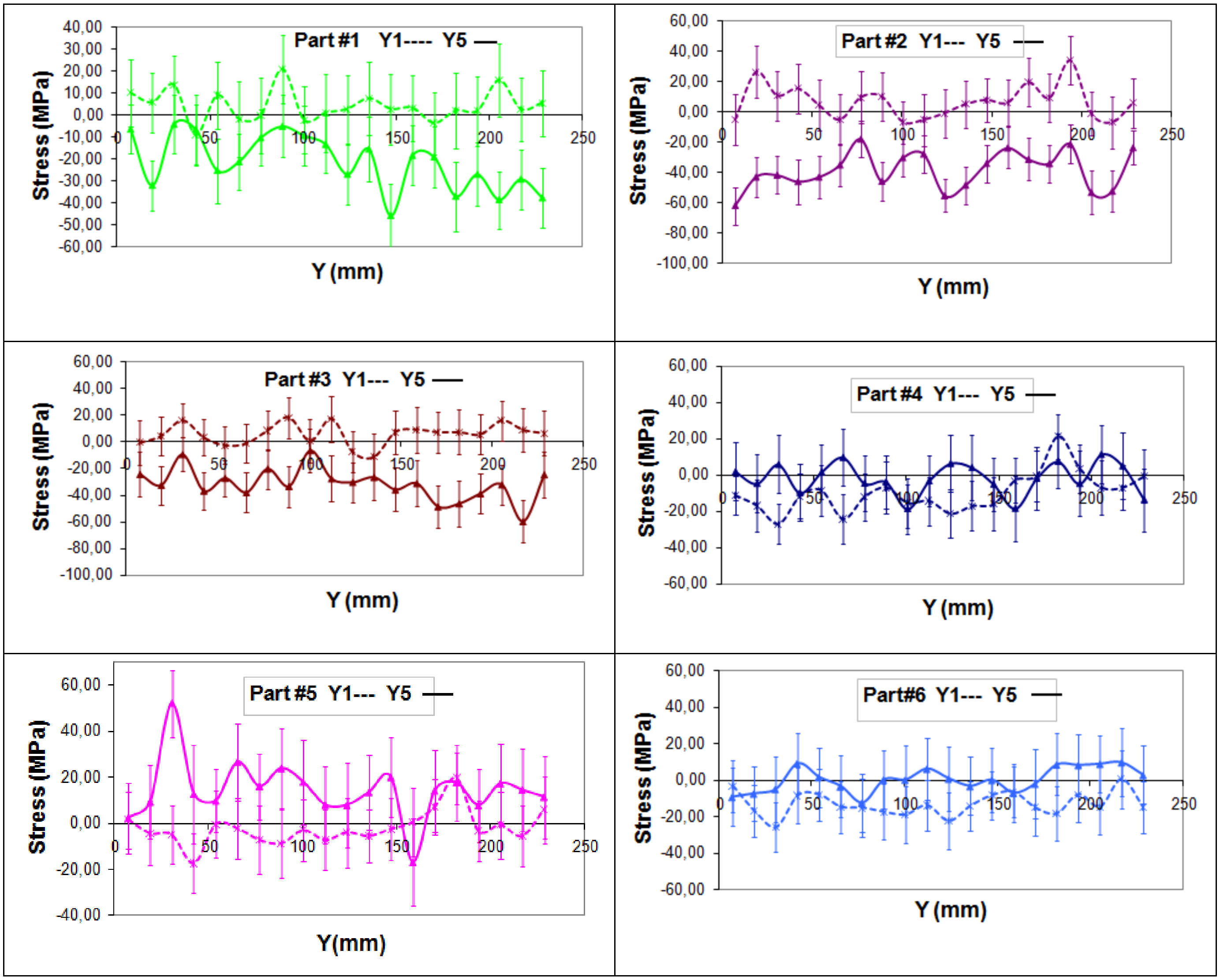

Fig. 8 Focus on normal component (X-axis) of residual stress along longitudinal direction Y1 (bottom) and Y5 (top) for standard material (#1, #2, #3) and controlled material (#4, #5, #6).

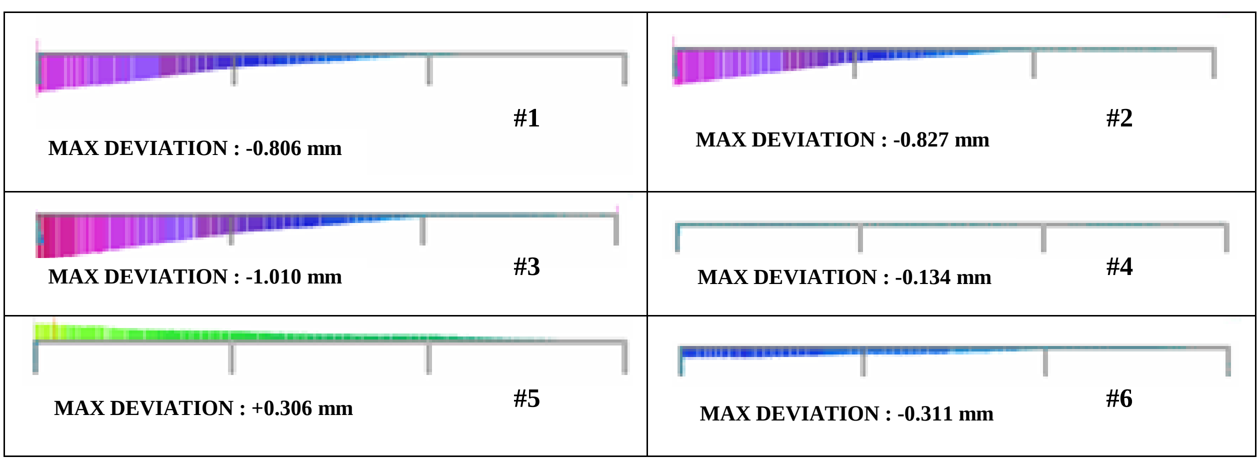

Fig. 9 Longitudinal cross-section of the machined part and representation of the deformation for standard material (#1, #2, #3) and controlled material (#4, #5, #6)

V. CONCLUSION

A comparison of part deformations after machining due to existing residual stresses in workpieces has been studied. The same aluminum alloy, but with different processing parameters, was used as a raw material for the machining process. The first alloy type was standard, while the second alloy was processed using a special recipe which lowers and standardises the residual stress levels within the material. The same cutting conditions and set-up were used, and new cutting tools were considered for all six parts machined. It was found that the initial stresses embedded within the raw material seemed to have an effect on the final part deformation. In fact, the stress distribution and magnitude, measured using a neutron diffraction method, seem to be related to the size of the deformation error. The study focused on the longitudinal deformation, which has been found to be significant compared to the other directions. The sampling size should be enlarged, in order to plot a complete 3D cartography for the stress distribution, and validate our conclusion. Regarding the residual stresses measured on the machined parts, they are also related to the final part deformations. Further study should isolate the residual stresses found due to the cutting mechanism and determine if these are large enough to overcome the elastic limit of the material, and whether they have a significant effect on the resulting deformation.

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