X-RAY COMPUTED TOMOGRAPHY AS A TOOL IN JOINING PROCESS DEVELOPMENT

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3-D information on defects in joints are of great importance. Computed tomography is a method that holds the promise of generating this information. This work shows several examples of application of CT on joining or joining related processes. The detection of foreign material, cracks and porosity is shown as well as the ability to investigate much larger volumes than what is feasible with traditional cut-ups. Some limitations are also discused.

Keywords: Computed tomography, Welding, Brazing, Friction stirr weldning.

1. INTRODUCTION

Understanding and detecting type, size and location of defects that different manufacturing processes may generate are important both for developing robust processes and for setting e.g. safety margins in the design processes of products. The need to correctly discover and define defects in 3-D is therefore eminent. One method that has the capability to detect both external and internal features and defects of materials and to generate 3-D information about them is X-ray Computed tomography (CT scan). The method is often described as a non-destructive method. This however depends on the material in question and what you want to detect. For detecting small features and defects, the samples have to be rather small in order to facilitate a significant magnification of the images. The ability to generate 3-D information of the internal structures, including defects, of materials without cutting the acual sample open is maybe the most powerful property of this method.

X-ray Computed tomography is a technology derived from conventional digital X-ray technology. The technology was first developed in the sixtied and seventies by Hounsfield (Ambrose & Hounsfield 1973) who also was awarded the Nobel prize for this development. At that time the development was focused on applications in the medical field. In medical applications it is used as a diagnostic tool to create images of the internal organs of the patient, often in the form of virtual 2-D slices. In industrial application the technology is used not only to produce images, but also to make 3-D models and to measure dimensions, both internal and external, of products. The basic principle of CT is the same for both areas. A large number of X-ray images are taken at different angles around the object to be investigated and these are then used to create a 3-D model of the investigated object by the use of back projection algorithms. The major difference is that in medical application the X-ray source and the detector is rotating around the patient while in industrial applications it is mostly the object to be investigated that is rotated. A comprehensive review of CT and how it works, especially for metrology, has recently been given by Kruth et al. (2011).

To investigate the feasibility of the method for inspection of larger components as well as materials samples from different processes a pilot study project has been conducted by Örebro University Campus Alfred Nobel, Bofors Test Center and four industrial partners. In this study, the applicability of X-ray computed tomography to manufacturing process development and quality control for several different materials and processes were investigated. The work reported here, is focusing on showing different application of CT joining or joining related processes.

The materials and processes that were investigated was taken from several different joining applications. Soldering and lack of bonding was investigated on a Ball Grid Array for electronic application. Welding was investigated for porosity in friction stir welds in aluminium. Other welding samples that were investigated were laser welding of iron based materials with a nickel diffusion barrier layer and weld penetration in laser welding of steel. For joining of composites to metals by bolt joints, the drilling of bolt holes is a critical process step. For this, fibre damage in drilled holes in CFRP composites was investigated.

2. EXPERIMENTALS

The X-ray tomography equipment used was an industrial CT system with a 225 kV X-ray source, a minimum focal spot size of 3µm and flat panel detector with 2000 x 2000 pixels at 16 bit. In this equipment samples up to 600 mm in height and 250 mm diameter can be handled. Power settings vary between the different materials, with lower settings for lighted materials and higher settings for heavier materials. For heavier materials the use of filtering to minimise beam hardening is also necessary. This also increases the need for higher power settings. In most cases 1500 images were taken during one revolution of the object. This results in a total scanning time of 25 minutes. For some samples up to 6000 images were taken. The resulting X-ray projections were used to reconstruct a 3-D volume of the investigated object using a filtered back-projection algorithm. In order to separate different materials and determining their interfaces, thresholding of the reconstructed volume using commercial software involving adaptive surface determination methods were used. Both surface and sub-surface defects were then analysed, taking advantage of the high-resolution 3-D reconstructed model showing different material in different grey-level voxels.

Three basic modes were used for examining the samples. Initially the 3-D volume were used both using adaptive surface determination methods and in a semi-transparent mode together with the void detection feature of the commercial software. This was used to investigate the ball grid array for soldering defects and for the porosity determination of welds as well as the hole surface feature determination in the drilled holes in the CFRP composite. The second mode used was the “virtual” 2-D slice that resembles a metallographic cut-up. This was used as a part of the investigations of weld penetration in the laser welding of steel and in drill induced defects in CFRP composite. The third mode is an extension of the 2-D “virtual” slice method. Here the virtual slice, or sectioning plane, is used to sweep around the cylindrical weld or the drilled hole and used to create a movie allowing for a full inspections of the feature in question, Figure 1.

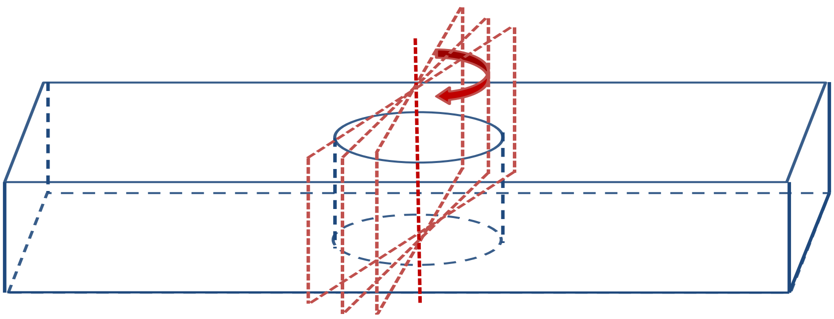

Fig. 1. Inspection of a hole by the use of sweeping a sectioning plane around is and creating a movie.

The materials used in friction stir welds were two aluminium alloys. The AA 6082-T6 is one of the stronger in the 6000-series and has good corrosion resistance. It contains Si, Mg, Mn and is heat-treatable. The other alloy, AA 5754 is an alloy for marine applications and contains Mg (2.5 - 3%) and smaller amounts of Si, Fe and Mn.

In the case of laser welding of iron based materials with a nickel diffusion barrier layer, 18CrNiMo7-6 was welded to a carbon steel with an intermediate layer of pure Ni as a diffusion barrier.

For laser welding of steel, a stainless steel lid was welded by two welds on a carbon steel cup.

The CFRP composite material investigated is a quasi-isotropic C fibre/epoxy-composite laminate. Each layer is about 0.25 mm thick, built according to [45/0/-45/90] fibre directions. In total 16 layers with the fibres (in bundles) in different directions is used. Each bundle contains about 12 000 fibres with a linear density of 800 tex (= 800 g/1000m). Each layer is held together by thin bundles of glass fibres. The C-fibres are TohoTenax HTS40 the glass fibers are E-glass and the epoxy is Hexcel HexFlow RTM6.

The drilling of this material has been performed with tools and parameters based on drill vendors recommendations. Details of drilling experiments are to be reported elsewhere (Beno et al. 2013).

3. RESULTS AND DISCUSSION

3.1. Ball Grid Array

A Ball Grid Array for electronic application was used as the example of inspection of soldering and lack of bonding. Here a macro was created in the software allowing for quick determination of poor or incomplete bonding of the complete area of the component. The example here, Figure 2, shows how powerful the X-ray tomography method can be in that it can for the same investigation create both a full overview of a complete component and give the possibility to zoom in on details for further and in depth analysis.

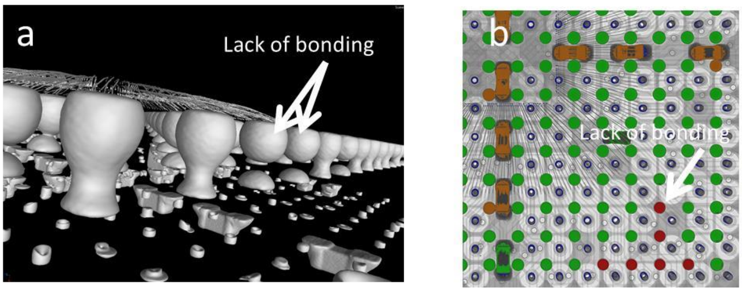

Fig. 2. Lack of bonding in soldering of a Ball Grid Array for electronic aplication, a) 3-D view showing two balls with no bonding, b) 2-D color mapping of a part of the component with red points showing no bonding, yellow points showing partially bonded and green points showing full bonding.

3.2. Friction Stir Weld Joint

The two aluminium alloys, AA 6082-T6 and AA 5754, used in friction stir welds does not have enough difference in density to allow for studying the mixing of materials in the weld. For materials with a larger difference this could be a question where the CT technology could be of interest. 3-D information of the mixing is an important parameter in the understanding of the process and could be a good candidate for validation of process models. Due to this similarity in density for the materials, the investigation was therefore directed towards detecting how far porosity associated with the start of the process is reaching into the weld.

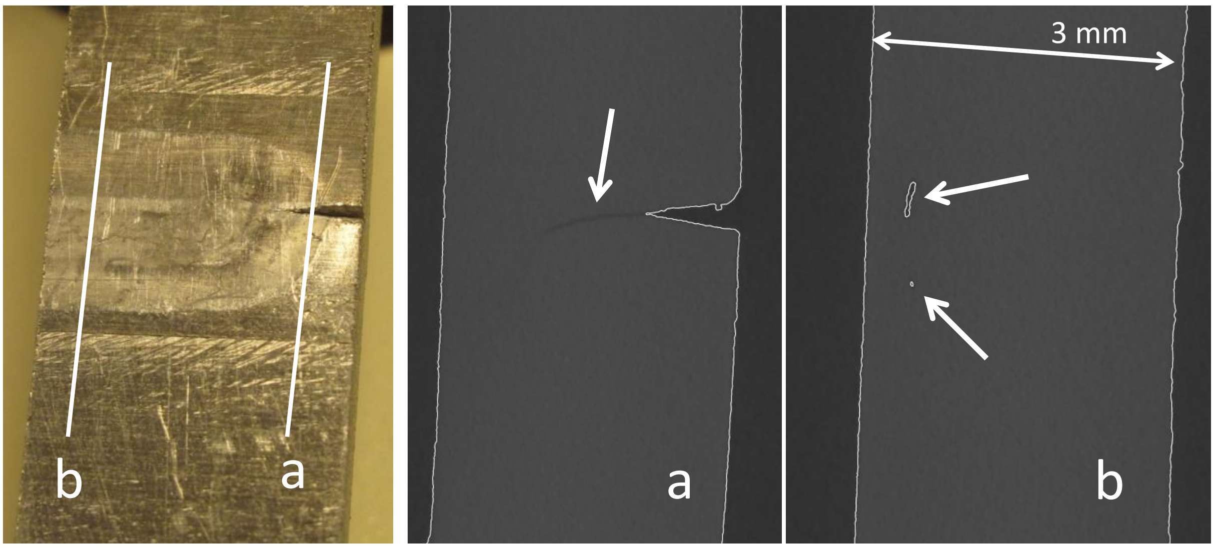

Fig. 3. Friction stir weld sample. Photograf (to the left) showing the bottom side of the start of the weld with the position of the virtual 2-D slices indicated. In slice a, a lighter material (presumably oxide from the surface) can be seen. In slice b, porosity is shown.

The first sample, Figure 3, was cut from the starting side of the weld and it was found that there was a lighter material underneath the region where the joint were not complete. This material is presumably oxide containing and is most likely a result of mixing into the joint oxide material present at the “pre joint” surface of the metals.

This material feature was also found to bend slightly and this is probably due to material flow patterns in the weld. Due to the density similarity of the two materials, the flow patterns could not be detected. With a suitable density difference between two materials in a FSW joint, the CT method could possibly be used to study such phenomena. A porosity stretching into the joint from the virgin joint surface was also found, Figure 3b. The "porosity trace" starts close to the un-bonded area and is close to the bottom (root) side of the joint and follows a path in the direction of the rotating direction of the tool. This porosity was further investigated, Figure 4, by cutting an additional sample in the direct continuation of the joint. To get the full picture of the joint the two samples were stitched together virtually, Figure 4, to be able to follow a "porosity trace" that was a possible final result from the partial results found in sample 1.

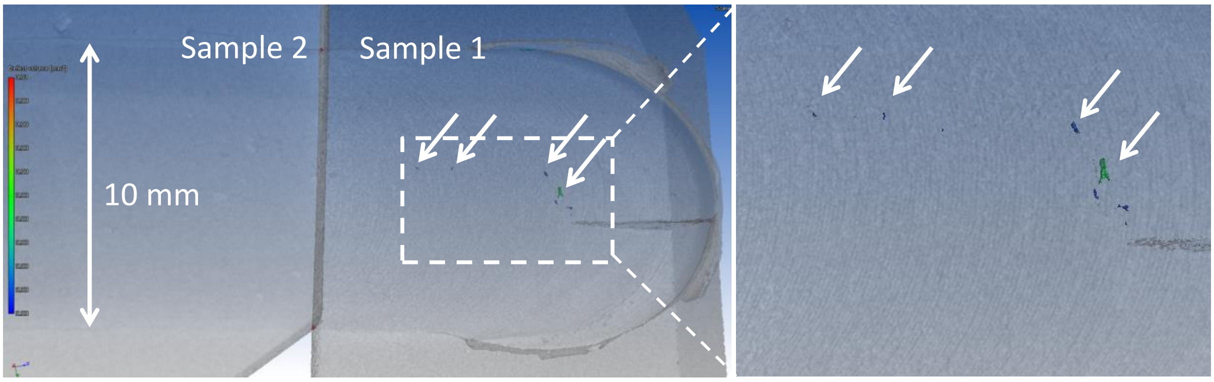

Fig. 4. Friction stirr weld sample analysed in two sections, using a 3-D volume in a semi-transparent mode and void detection, and a magnification of the porosity found in sample 1.

Sample 2 in Figure 4 does not show any porosity in this investigation. The sample #2 reaches out extensively to the left of the figure. A total investigated length of the joint of 60 mm, coresponding to more than 6 times the with of the joint, was used. Thus a large volume of the FSW joint has been investigated to form the basis for the conclusions. The results from this investigation is that the porosity found in the joint of two different aluminium alloys, AA 6082-T6 and AA 5754, is only associated with the early phases of the friction stir weld process.

3.3. Laser Welds

Two laser welding processes were investigated. In the case of laser welding of two iron based materials, a carbon steel and a stainless steel, with an intermediate pure nickel diffusion barrier layer, porosity in the nickel layer was detected, Figure 5. Again, the materials used do not have enough difference in density to allow for detecting possible mixing of materials, in this case inter-diffusion, in the weld. The porosity that was detected is distributed fairly regular along the length of the weld and on the root side of the weld. The porosity is most likely a result of shrinkage as the Ni solidifies upon cooling. The size and shape of the pores are easily distinguished with the CT methodology.

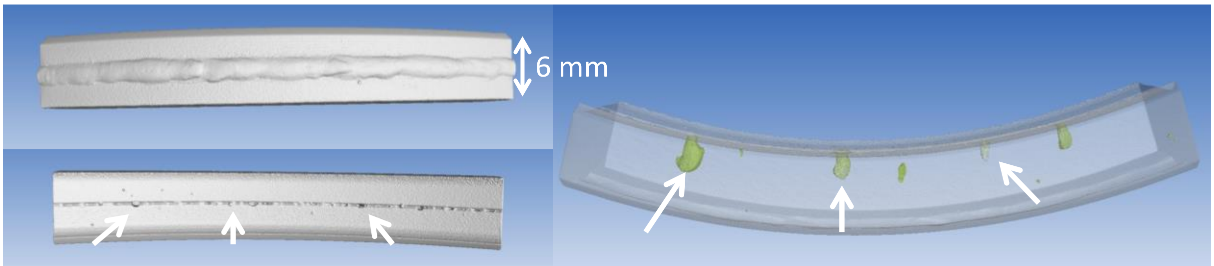

Fig. 5. 3-D volume of a laser weld sample of two iron based materials, a carbon steel and a stainless steel, with an intermediate pure nickel diffusion barrier layer. The prorosity detected (colored in green) is asociated with the Ni diffusion barrier.

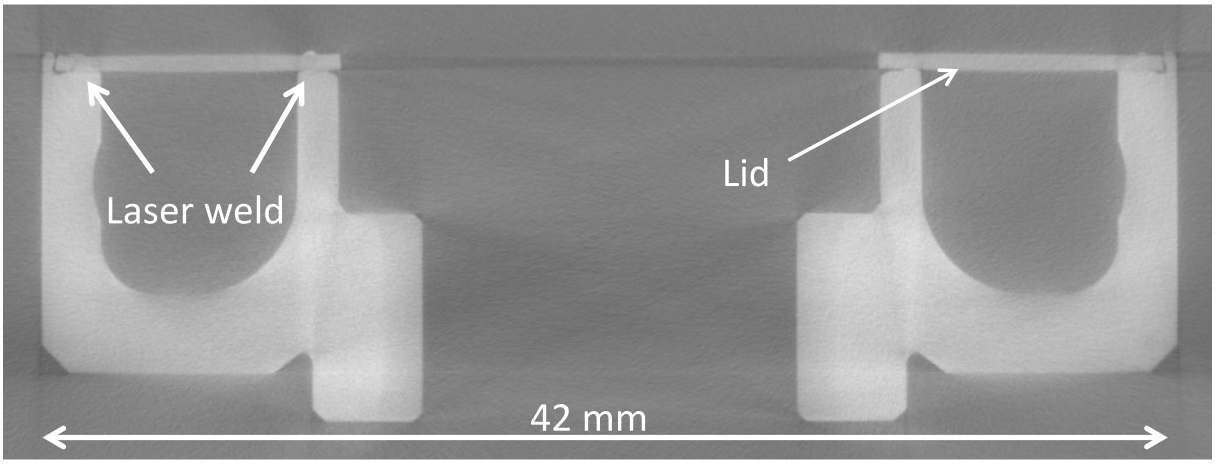

Fig. 6. A virtual 2-D slice of two laser welds of steel (stainless steel lid welded on a carbon steel cup).

In the case of the stainless steel lid welded on a carbon steel cup, the CT scan was used to create a 3-D volume and from that, the welds were investigated by constructing a virtual plane and sweeping this around the reconstructed component in the area of the weld, Figure 1. This technology is shown to be quite powerful in the ability that it allows for the possibility to cover larger volumes in the inspection. By this it is possible to cover the complete volume of interest. The result from this is quite difficult to show in the 2-D form that a paper is restricted to. Figure 6 shows only one virtual slice of the total 360 degree lap that was covered. The welds were found to have complete penetration, but a variation in the width of the bond in the transition from lid to base material in the cup could be followed around the weld lap. In this case this variation is within the specification, but it is quite clear that in a situation where this might be a critical feature, traditional inspection methods such as cut-ups may well miss to detect critical variation.

3.4. Drilled holes in CFRP coposite

In drilling of CRFP composites, there is several common potential damage types associated with the layer structure of the material. One of these damages, which are of high importance, is delamination. This comes from the inherent properties of the material, which is strong in the direction of fibres but quite weak perpendicular to this direction. Thereby the material is susceptible to cracking between layers. Delamination is a type of damage that is difficult to detect in optical microscopy. It occurs primarily at the entrance side or exit side due to pull or push forces from drilling process and tool respectively. Other types of damages are fibre pull-out and fibre cracking which is a damage that occurs inside or on the surfaces of the material as a cause of the torque movement of the drill. These damages, as shown in Figure 7, were studied by using the same technique of sweeping a virtual plane around the reconstructed hole as described for the welded cup, Figure 1.

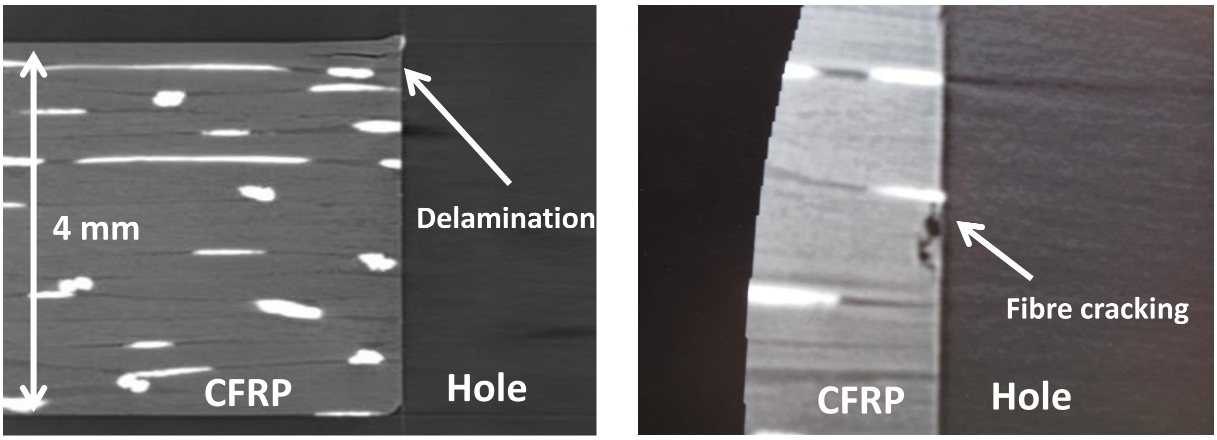

Fig. 7. Two virtual 2 D slices of drilled hole in CFRP composite.

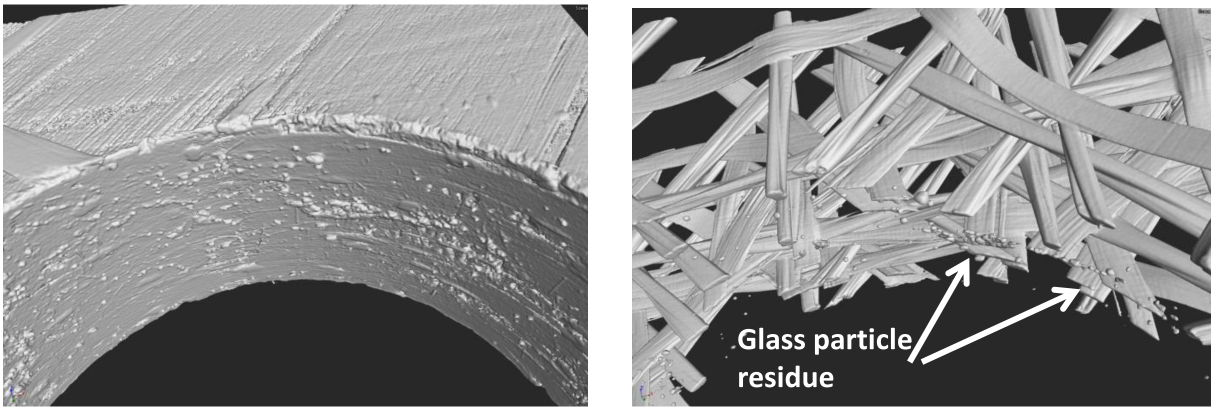

Fig. 8. Reconstructed 3 D volume of the drilled hole in 4 mm thick CFRP composite. To the left showing surface detection view. To the right with all material exept glass removed.

In the composite case, the density differences between the carbon fibres, the epoxy resin and especially the glass fibres, made it easy to distinguish between the different materials in the CT scan information. By using this, glass residue from cracked glass fibres, was detected on the surface of the hole. This glass residue can be quite harmful to the intended joint in which a bolt or a bushing is pressed into the hole. In such a case, these particles may be pressed into the hole wall and act as crack initiation sites both as stress concentration sites and as "hardness indenters". A more thorough comparison of optical inspection methods and CT of drilled holes in CFRP is given by Pejryd et al (2014).

3.5. Dimensional measurements

The measurement of dimensions using CT systems is not entirely straight forward but can be quite accurate. When using a metrological CT system it is generally possible with sub-voxel accuracy, as demonstrated by Carmignato (2012). However in the specific case of this work, where the CT scan is more used as a "3D microscope", the system is not especially designed for metrology and the focus was not to extract exact dimensions of the defects detected but rather to show the general capability of the CT method in examination of defects in joining applications. The equipment and methods used in this work does therefore result in a relatively poor accuracy for the dimensions. If this is important the methods used must be adopted for more accuracy by e.g. working with calibration objects in the same scan as the sample to be investigated.

4. CONCLUSIONS

Computed tomography (CT scan) is shown to be a promising method to evaluate different joining applications.

One of the main advantages is that the CT method can cover much larger volumes in the inspection for surface and sub-surface defects than many other methods such as traditional metallographic methods.

The method also holds the potential of quantification of defects both for size and shape in a way that most other methods does not. The CT scans show clearly both porosity and cracks both in surface and in sub-surface regions. It can also show delamination damage in CFRP composite materials.

When highly accurate data on dimensions is needed, the use of calibration objects can be used. In such cases a specially designed metrological CT system may be preferable. Using such a system, it is generally possible to reach sub-voxel accuracy.

Due to sample size and resolution relations, the method described here for detection of relatively small defects in joining applications, may mostly be interesting for use in the development stages of new products and processes. For these purposes it may have its limitations for use on large components.

ACKNOWLEDGEMENTS

The work reported here was mostly conducted within a study that was financially supported by Länsstyrelsen in Örebro län. This support is greatly acknowledged.

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