Laser Ultrasonics for Examination of Defects in Aluminium Profiles

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Abstract. Laser-Ultrasonics (LUS) provides a means of obtaining microstructure information and NDT data continuously in both in the laboratory industrial quality control systems. Ultrasound is generated and recorded using lasers, which permits remote, non-contact operation and the capability of working at high temperatures or/and with at moving surfaces.

This paper reports results from experiments aimed at industrial in-line applications during processing of aluminium. The investigations cover LUS abilities to detect possible defects in extruded profiles and in friction stir welds (FSW). The results show that LUS is a potential tool to use for these applications although data interpretation may be complicated. Compared to other NDT devices, the LUS approach has unique and considerable advantages due to its remote operation, especially when complemented with fiber optics. This enables operation under conditions where transducer and EMAT devices are difficult or impossible to implement.

1 Introduction

Ultrasonic waves that travel through a metal sample interact with the microstructural features, so that the registered wave spectrum will carry microstructural information about the penetrated volume. In traditional applications of non-destructive testing, the data analysis is focused on the possible presence of echoes of waves. An echo may indicate that the wave met an obstacle (a defect) and the echo's time of flight provides information on the obstacle's location. A more descriptive analysis is achieved by studying the velocity, attenuation and dispersivity of the wave. The work presented here is focused on classical NDT applications, where relatively cheap and robust piezoelectric transducers and EMAT-coils traditionally dominate. However, such devices suffer from the fact that both sensor and actuator need to be either very close to or in direct contact with the specimen examined, while LUS permits true non-contact operation, which enables measurements in aggressive environments and on moving surfaces. Considering aluminium products, there are several fields where non-contact systems for in-line quality control could be applied. In this report, we present investigations of LUS abilities to detect possible defects in extruded aluminium profiles and in friction stir welds.

Extrusion is a process that is extraordinary feasible for manufacturing of tubes, bars and complex profiles in aluminium, which is a major reason to the vast importance of aluminium as a construction material. The extrusion process is schematically shown in Figure 1: preheated aluminium billets are forced through a die that forms the final shape to the profile. Although the process is effective and reliable, some defects can appear at the interface between individual billets. The interface between the billets is called the charge weld and consists of oxides and cavities that impair the mechanical properties of the profile. To maintain required quality, these defective parts of the profiles have to be removed.

Friction stir welding (FSW) invented by The Welding Institute (TWI) [1] is widely used for joining aluminium alloys. A friction stir weld is formed by plunging a specially designed, non-consumable rotating tool into the faying work-pieces until the tool shoulder is in contact with the work-piece surfaces (Figure 2). Due to friction the rotating tool heats the metal at the interface of the work-pieces. Eventually, the metal becomes plasticized without reaching the melting point. The rotation of the tool enables stirring, mixing and transferring of the material around the tool, thus creating a joint. It has been shown that FSW is able to produce welds that exhibit superior metallurgical and mechanical properties [2]. However, deviations from the optimum welding conditions can cause defects in the joints. For instance, an insufficient tool plunge depth during the welding results in flaws, the defects that are associated with a lack of penetration. Gaps or a thickness mismatch between the work-pieces can initiate cavities, the defects inside of the weld body.

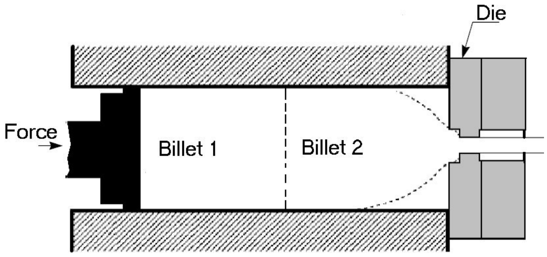

Figure 1: Schematic of the extrusion process of aluminium.

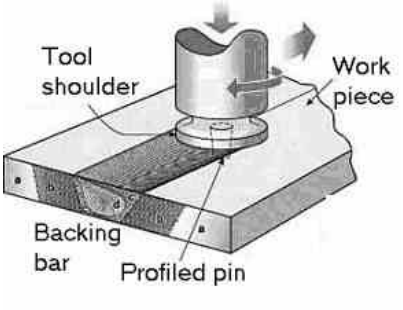

Figure 2: Friction stir welding process invented at TWI (reproduced from [2])

2 Ultrasonic waves in solids

Ultrasonic waves are found in a wide variety: e.g. bulk waves, surface waves and guided waves. The distinction between the different types of ultrasonic waves in a solid is based on two criteria: the direction of particle displacement with respects to the wave propagation direction and the geometry of the medium respectively. Bulk waves are waves propagating in an unbounded solid i.e. a solid whose dimensions are much larger than the wavelength. A half-space transmits three bulk waves, one longitudinal (P wave) and two shear waves (transverse or S waves) with orthogonal polarisation. A surface wave propagates in the interface between a half-space and a rarefied medium. The best-known surface wave is called *Rayleigh wave.* The penetration depth of a Rayleigh wave is proportional to the wavelength and the penetration depth is of about a wavelength. If a solid is bounded by two parallel surfaces a wave can propagate along the material by a series of consecutive reflections from these surfaces. This type of wave is called a *guided wave* [3].

Ultrasonic waves that travel through a metal sample interact with the microstructural features, so that the registered wave spectrum will carry microstructural information about the penetrated volume. In steel for example, the ultrasonic velocity depends on the average elasticity of the solid while properties such as grain size and second phases may affect the frequency dependence of the attenuation. In previous studies [4], LUS applications aimed at in-line monitoring and control of microstructure properties of metals have been considered. These included real-time monitoring of phase transformation, recrystallisation and grain growth, measurements of the grain size and elastic properties.

3 Laser generated and detected ultrasound

The ultrasonic wave is generated by illuminating the examined object with a short (<10ns) laser pulse that heats the metal surface very rapidly. This localised heating promotes thermal expansion and ablation, which generates elastic waves that start to propagate along the surface and through the sample. All modes of vibration are generated simultaneously with frequencies that ranges several hundred MHz. For transducer based sources there are relatively cheap ways to direct the wave field in a specific direction by using angle beam transducers or phased array techniques. This allows for inspection of hidden or difficult areas of a part that cannot be accessed by normal incidence sources. The technique is applicable for laser sources [5] too but there are very few commercially systems available.

The laser based detection system works using an interferometric approach. There are two types of detectors. In the first type (Michelson interferometers), the light scattered from the surface is made to interfere with a reference beam. This gives a measure of optical phase and hence surface displacement. Detectors of the second type (Fabry-Perot detectors [6]) detect changes in frequency of the scattered light and give a measure of the surface velocity. A detector of this type was used in the present experiment.

4 Experimental approaches

4.1 Laser Ultrasonics at KIMAB

The equipment for generating and detecting ultrasonic waves at KIMAB was designed and built by Accentus in England and was installed at KIMAB in February 2001. An overview of the system is seen in Figure 3.

The excitation laser is a Continuum Surelite I (1064nm, 450mJ/pulse, pulse width 6-7ns, repetition rate 20Hz) and the detection laser is a Coherent Verdi V5 (532nm, single frequency, 5W cont). The ultrasonic detector is a confocal Fabry-Perot that reads the Doppler shift of the reflected light due to the ultrasonic vibrations in the specimen. The interferometer works in either transmission or reflection mode and can detect frequencies up to 100MHz. The laser system is complemented with a powerful system for resistance heating and a stepper motor that enables precise positioning of the sample.

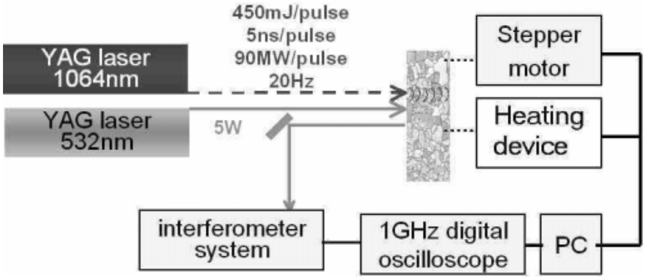

Figure 3: Overview of the LUS system at KIMAB.

4.2 Detection of extrusion defects

In a solid defect-free profile, a P-wave will propagate unimpeded through the sample. This is illustrated in Figure 4a, where the echoes appear at a time interval that matches the sample thickness. Defects in the form of cavities in the structure will impede and reflect the propagating wave (as shown in Figure 4b, where the short period of the echoes indicates that there is an obstacle in the specimen). If the profile contains an intermediate layer, for example an oxide layer, one part of the P-wave will be reflected while the rest of the wave will propagate through the entire thickness (see regular echoes that match thickness and extra echoes arriving more frequently in Figure 4c).

The examined specimen used in this study was a rectangular 10×80mm profile of the EN AW-6063 alloy. P-wave measurements were used for detecting defects. The excitation and detection were performed on one side, at about 1mm apart. The excitation beam was focused as a line. An area of 80×80mm was investigated in a region where defects were expected to be present.

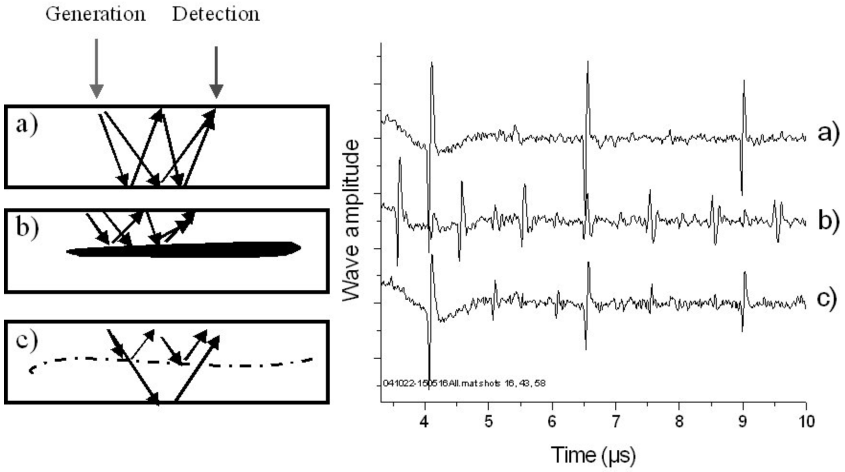

Figure 4. Defect detection using P waves in an extruded profile. a) no defects. b) cavity. c) intermediate layer.

4.3 Detection of defects friction stir welds

Manual transducer-based ultrasound methods are currently used for examination of the weld joints. The operation is not automated and time consuming. To investigate whether the LUS-technique can be used for detecting defects in the weld line, several experiments have been designed. The first part of experiments focuses on detection of incomplete weld joints, while the second part deals with cavities in the joint.

Two welds were produced on 3-mm thick flat profiles of EN AW-6082 aluminium alloys. One weld was a full penetration weld, i.e. the length of the tool pin was equal to the profile thickness. Another weld was produced with artificial lack of penetration using a pin being slightly shorter than the profile thickness (see Figure 5b). Both welds were ~220mm long and ~14 mm wide. The joint lines were examined using Rayleigh waves propagating over the bottom side of the weld seam and an incomplete weld was then expected to subdue the Rayleigh wave. The generating laser beam was focused as a line parallel to the weld seam and measurements were made at intervals of 1mm alongside the weld joint.

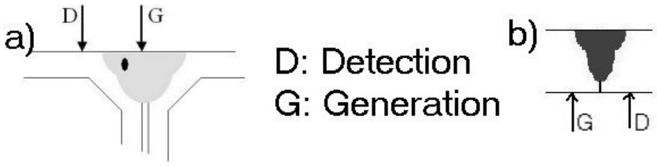

Figure 5: a) A cavity in the weld. b) Incomplete penetration of the weld.

The sample material used for detection of cavities in the joint was a piece consisting of two extruded profiles that were joined by FSW. The sample was ~600mm long and the gap width increased from 0 to 1.5mm from end to end. This resulted in a joint that gradually evolved from being defect-free to defective. Bulk waves generated with a line focus close to the centre of the weld were studied in the weld examined. The detection was performed at 5-7mm next to the centre line, on the advancing side of the joint (Figure 5a). A defect was recognised when an extra echo was detected.

5 Results

5.1 Defects in extrusions

In order to map profile integrity, each signal type (see Figure 4) was given a certain symbol that was plotted in a diagram versus position on the sample. The map obtained is shown in Figure 6*a,* where dots indicate total penetration and defect-free zones, while encircled dots indicate an intermediate (oxide) layer and crosses correspond to a cavity. The measurements show that there are both intermediate layers and some cavities in the internal structure. Considering the form and location of the defects, one could assume that the detected cavities and intermediate layer arise from the tip of the charge weld. An estimated shape of the charge weld is depicted as a dashed line in Figure 6*a.* The map is completed with an optical micrograph of the cross section in Figure 6b.

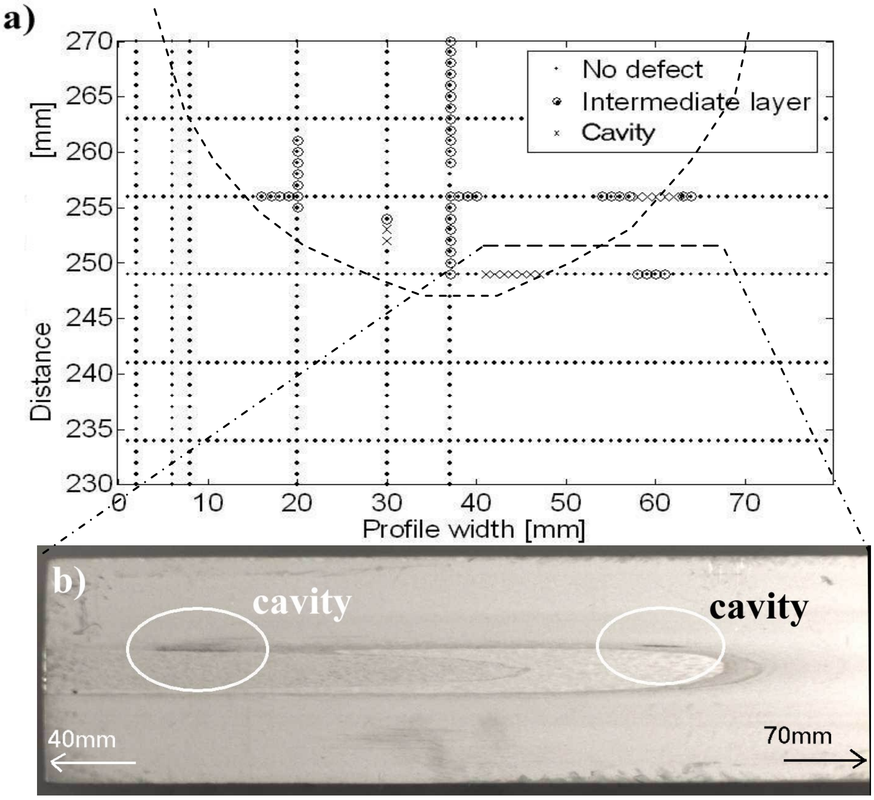

Figure 6: a) Integrity map of the extruded specimen examined. The dashed line shows the probable shape of the charge weld. b) Optical micrograph from the cross section of the extruded specimen

5.2 Defects in friction stir welds

In the experiments on detection of incomplete weld joints, the Rayleigh wave was set to propagate across the bottom of the weld line (Figure 5b). A possible crack or a gap was then expected to affect the properties of the Rayleigh wave. In Figure 7a, the amplitude of the negative peak of the Rayleigh wave is shown as a function of distance along the weld line. It is seen that the signal from the defect-free weld shows smaller scattering of the signal amplitude than the corresponding signals from the weld line with incomplete penetration. Figure 7b shows an etched cross section of the defective weld at 130mm. The first part of the crack, 0.4mm, is a result of incomplete penetration, but then the crack turns off and follows the entrapped oxide layer.

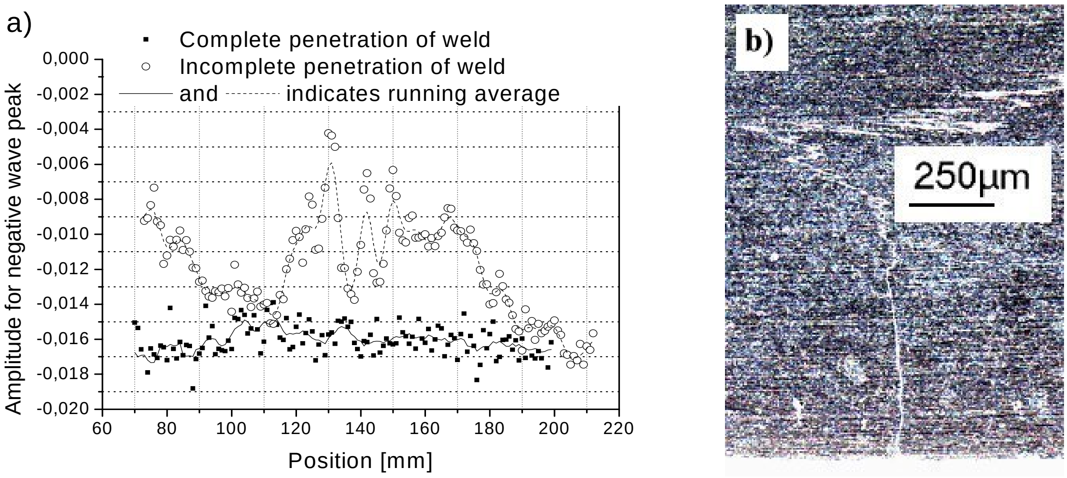

Figure 7: a) Amplitude of the negative peak of the Rayleigh waves from weld lines with complete and incomplete penetration. b) A picture of the cross section of the defective weld at 130mm.

For detecting internal cavities in the joint (Figure 5a) bulk wave echoes were analysed. If a defect is present, there will probably be an extra echo. The results are shown in Figure 8 in shape of a B-scan, where the grey scale indicates wave peak amplitude and white/black indicates positive/negative peaks. The graph shows a constant echo at 1.5µs arising from reflections at the walls of the joined profiles. The defect is present at about 1.7µs and 330-550mm.

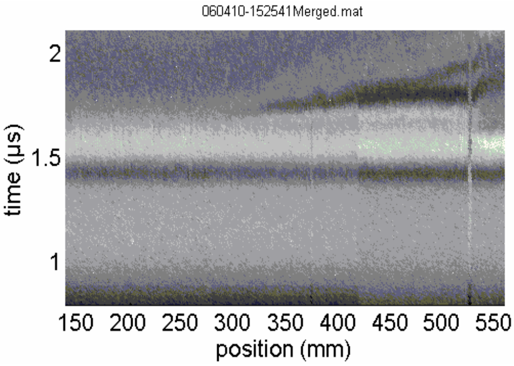

Figure 8: A B-scan from the FSW-joint. A defect is detected at 1.7µs and 330-550mm

6 Discussion

The general impression from the experimental results is that laser ultrasonics has potential to serve as a tool for quality inspection within manufacturing of aluminium products. However, except for the experiments concerning cavities in the weld joint, the geometry of the examined samples were very simple and the responding wave forms were easy to interpret. A general extruded profile may have a complex geometry resulting in a wave trace with echoes from many walls. Therefore, the positioning of the lasers has to be carefully chosen to provide a waveform that excludes most of the unwanted echoes. Despite this, the response may sometimes be too complex to render possible defect detection by just taking a look at a single wave trace. Instead, detection is done by identifying unexpected relative changes as a function of position along the weld.

The experiments concerning defect detection in extruded profiles showed that laser ultrasonics is a straightforward and reliable method to implement for the simple geometries examined. Profiles with complex geometry will most likely be more difficult to examine. However, the location of extrusion defects may be controlled and positioned to specific spots in a profile by choosing an appropriate design of the extrusion tool. Under such conditions, laser based methods have good opportunities to be successful for this application.

The results indicate that defective FSW joints with incomplete penetration of the weld can be identified by studying the amplitude of the Rayleigh wave. An insufficient penetration results in considerable amplitude variations. It should be possible to identify this behaviour by studying relative changes in the wave trace although some experience is required to recognise the level of intolerable variations. It is also possible (although not easy) to detect cavities in FSW welds when analysing relative changes in the ultrasonic wave trace, for example, in a B-scan. The specimen examined had a complex geometry that generated numerous echoes. To make the method successful, the lasers have to be applied at a precise and constant position with respect to the weld seam.

7 Conclusions

The experiments show that laser ultrasonics may be used for detection of different types of defects in extruded profiles and FSW welds. Laser based ultrasound method is a true non-contact technique, which enables measurements on hot samples, in aggressive environments and limited spaces. Extruded aluminium profiles with complicated geometries can generate a rich response to an ultrasonic pulse. To minimize the amount of irrelevant echoes, the geometric configuration of the lasers has to be carefully considered. For simple geometries a defect can be detected by studying a single wave trace, while for more complex profiles it is necessary to rely on relative changes as a function of position along the sample. An alternative is to use phase array technique that can focus the wave field on a specific area of interest.

Acknowledgements

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References

[1] http://www.twi.co.uk/j32k/unprotected/band_1/fswintro.html
[2] J. Backlund, Å. Andersson, A. Norlin, Friction stir welding – weld properties and manufacturing techniques, INALCO 1998, 7th International Conference on Joints in Aluminium, Cambridge, UK
[3] D.Royer, E.Dieulesaint, "Elastic Waves in Solids",Springer-Verlag (2000)
[4] M.Ericsson, E.Lindh-Ulmgren, D.Artymowicz, B.Hutchinson, "Laser-Ultrasonics (LUS) for Microstructure Characterisation", SIMR-report IM-2003-113, Stockholm
[5] S.N.Hopko, I.C.Ume, D.S.Erdahl, "Development of a Flexible Laser Ultrasonic Probe", J. Manuf. Sci. Eng., vol124, pp. 351-357
[6] C.B.Scruby, L.E.Drain, "Laser Ultrasonics: Techniques and Applications", Adam Hilger (1990)