Proc. Vth International Workshop, Advances in Signal Processing for Non Destructive Evaluation of Materials
Québec City (Canada),2-4 Aug. 2005. © X. Maldague ed., É. du CAO (2006), ISBN 2-9809199-0-X

Keynote lecture

Characterization of Microstructures in Metallic Materials using Static and Dynamic Acoustic Signal Processing Techniques

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Abstract

In this paper, application of ultrasonic techniques for defect detection in weldments of austenitic stainless steel and maraging steel is discussed. Applications of ultrasonic techniques for characterizing microstructural changes in AISI type 316 stainless steel and modified 9Cr-1Mo ferritic steel; thermomechanical processing of 15Cr-15Ni-2.3Mo-titanium modified austenitic stainless steel (alloy D9) and isothermal annealing behaviour of alloy D9, are discussed. Applications of acoustic emission technique for fatigue crack growth studies in 316 stainless steel and for on-line monitoring of forging of Al alloys are also discussed.

1.0 Introduction

Non-destructive evaluation (NDE) techniques such as ultrasonic and acoustic emission are employed for detection of defects and microstructural characterization in materials. Broadly speaking, while ultrasonic techniques are used for detection of static changes in materials, acoustic emission technique (AET) is used for revealing the dynamic changes occurring in the materials. In this paper, application of ultrasonic techniques for defect detection in weldments of austenitic stainless steel and maraging steel, where detection of defects using ultrasonic testing is a significant challenge because of poor signal to noise ratio of the ultrasonic signals associated with dendritic (hence anisotropic) microstructures of the weldments, has been discussed. Applications of ultrasonic techniques based on time and frequency domain signal analysis for characterizing microstructural changes in materials such as grain size in AISI type 316 stainless steel and modified 9Cr-1Mo ferritic steel, thermomechanical processing of 15Cr-15Ni-2.3Mo-Ti modified austenitic stainless steel (alloy D9), isothermal annealing behaviour of alloy D9, etc. are discussed. Applications of AET for fatigue crack growth studies in parent and weld specimens of AISI type 316 stainless steel and for on-line monitoring of forging of Al alloys, are also discussed.

2.0 Application of Ultrasonic Techniques for Defect Detection in Weldments

Industrial components in many chemical, petrochemical, process and nuclear industries are made of stainless steels. Detection of defects in welds of stainless steel with textured and dendritic structure, using ultrasonic testing poses a great difficulty because of poor signal to noise ratio of the ultrasonic signals. The noise due to grain scattering dominates the signal corresponding to a defect. Therefore, advanced signal analysis concepts such as spectral analysis, pattern recognition and neural network analysis are employed in such cases. Dendritic (hence anisotropic) microstructures of stainless steel weldments, especially in the thickness range of 10 to 40 mm pose problems for ultrasonic testing. Considering these facts, the ASME boiler and presser vessel code has recommended that in the case of austenitic stainless steel weldments, any defect that is 10 % of thickness should be recorded and monitored. In some cases, it may be desirable to detect defects of less than 10% of the thicknesses. In this connection, signal analysis (SA) procedures, by using effective cluster and pattern analysis algorithms have been developed, in the authors' laboratory [1,2]. These enable detection and characterization of defects down to 1% of weld thickness (14.0 mm weld thickness) in austenitic stainless steel welds. The pattern analysis method generates a pattern called demodulated auto-correlogram (DMAC) from the auto-correlation function of a signal. Features of DMAC are studied for interpretation and evaluation. In Fig.1, ultrasonic signal patterns of typical noise, porosity, notches and cracks in austenitic stainless steel welds are shown [2]. In case of maraging steel weldments used in rocket motor casings by aerospace industry, tight cracks (3 mm X 1 mm) produced by fatigue loading were detected and characterized using cluster and pattern analysis principles (Fig.2). Detection of such small cracks enables in reducing wall thickness of the rocket motor casing and hence in decreasing weight to thrust ratio of the casing. In both the cases, the cluster and pattern analysis methods use the cross-power spectrum (between signals from weld noise (Fig.2a) and those from the defects (Fig.2b)), to obtain the cluster elements.

3.0 Application of Ultrasonic Techniques for Grain Size Measurement

The ultrasonic spectral analysis based methodologies have been developed for grain size measurement in AISI type 316 stainless steel and modified 9Cr-1Mo ferritic steel [3]. Amplitude of ultrasonic signals for different grain sizes and correlation of peak frequency (PF) and frequency at full width half maximum (FWHM) of ultrasonic signals and yield strength with grain size for this steel are shown in Fig.3. For the first time, the importance of spectral characteristics of different ultrasonic transducers has been brought out for assessment of grain size in materials with differing elastic anisotropies and hence different scattering powers. It has been demonstrated that the transducer exhibiting single peak in the autopower spectrum of the first backwall echo should be used for higher scattering materials, such as austenitic stainless steels, whereas the transducer exhibiting double peak should be used for lower scattering materials, such as ferritic steels.

4.0 Characterization of Microstructural Evolution during Thermomechanical Processing of 15Cr-15Ni-2.3Mo-Ti Modified Stainless Steel using Ultrasonic Technique

Ultrasonic velocity and attenuation measurements have been carried out on a 15Cr-15Ni-2.3Mo-titanium modified austenitic stainless steel (alloy D9) after thermomechanical processing. The cylindrical specimens of alloy D9 were subjected to upsetting at 1273 K for various strains in the range of 0.1 to 0.5 in a hydraulic press. The upset samples were then analyzed for microhardness for predicting the extent of recrystallization during processing. The microstructural examination was carried out to obtain the grain sizes of the samples with the processing history. A slice of 4 mm thickness was cut along the forging axis using electric discharge machining for all the test conditions. The upsetting develops dean metal zone, two perpendicular intense shear zones at 45^0 to the loading direction and deformation zone in the specimens. Autopower spectra of the first back wall echoes obtained in slices 0-5 is shown in Fig.4a. While peak frequency and ultrasonic velocity for slices 0-5 are shown in Fig.4b. It has been found that ultrasonic attenuation and spectral analysis of the first back wall echo can be used for the evaluation of grain size, whereas, ultrasonic velocity is mainly influenced by the presence of texture and hence the extent of recrystallization. An important observation made is that the sample upset to a strain of greater than 0.4 resulted in very fine grain size in the intense shear deformation zone. In the sample upset to a strain of 0.5, the ultrasonic attenuation measurements indicated the presence of fine grains in only one intense shear region, which was later substantiated through metallographic studies. The results bring out the potential of ultrasonic measurements for characterizing the nonuniform deformation due to asymmetry in loading, strain distribution and extent of rectystallization during thermomechanical processing of 15Cr-15Ni-2.3Mo-titanium modified austenitic stainless steel.

5.0 Ultrasonic Velocity Measurements for Characterization of Annealing Behaviour of Cold Worked alloy D9

Ultrasonic velocity measurements using 4MHz shear waves have been carried out on 20% cold worked (tensile pulled) and annealed specimens of alloy D9 to characterize the isothermal annealing behaviour [4]. Shear velocity measurements have been made in all possible directions with reference to cold worked and wave polarization directions. Velocity ratio parameters (VS3-VS2)/VS3, (VS3-VS1)/VS3 and (VS2-VS1)/VS2 were established and plotted against the annealing temperature (Fig.5). In Fig.5, the fraction recrystallised microstructures with annealing is also plotted. In the velocity ratio parameters, VS1 is the shear wave velocity measured parallel to the tensile pulling direction, VS2 is the shear wave velocity measured perpendicular to tensile pulling direction but polarization parallel to pulling direction and VS3 is the velocity perpendicular to tensile pulling direction with wave polarization perpendicular to tensile pulling direction. A velocity parameter (VS3-VS1)/VS3, which is a combination of the shear wave velocities measured in the transverse direction with polarization directions parallel and perpendicular to the cold worked direction was found to closely represent the extent of recrystallization (Fig.5). The velocity measurements could sense the onset, progress and completion of recrystallization more accurately compared with that of hardness and strength measurements. It has been found that the variation in velocity with annealing time is similar at different frequencies (2, 10, 20 MHz) of the ultrasonic waves used for velocity measurements.

6.0 Acoustic Emission Technique (AET) for Fatigue Crack Growth Studies in AISI type 316 Stainless Steel

AET, which gives information on the dynamic changes such as plastic deformation and crack propagation, can be applied for continuous monitoring of fatigue crack growth (FCG) [5]. During FCG, the major source of AE for a ductile material could be the cyclic plasticity occurring ahead of the crack tip, whereas, for brittle materials, the crack extension at the crack tip could be the major source of AE. Apart from this, the presence of second phase precipitates, inclusions, residual stress induced microcracking in weld structure etc. can significantly influence the AE activity during fatigue crack growth.

Acoustic emission behaviour during fatigue crack growth (FCG) in parent and weld specimens of AISI type 316 stainless steel has been studied. Variation in cumulative ringdown counts (N) and crack growth rate (da/dn) as a function of cyclic stress intensity factor (ΔK) for 25 mm thick solution annealed (SA) and thermally aged (TA) specimens of 316 stainless steel has been shown in Fig.6. AET can be applied to distinguish the transition from sub stage IIa to IIb during stage II FCG by observing a sharp decrease in AE activity in both parent and weld specimens. The transition point in the cumulative ringdown count vs ΔK plot coincides with the da/dn vs ΔK plot. The AE activity increases with increase in ΔK during stage IIa and decreases during stage IIb. The increase in the AE activity with increase in ΔK during stage IIa is attributed to the increase in the size of the cyclic plastic zone (CPZ) which is generated and developed only under plane strain conditions. The decrease in the AE activity during stage IIb is attributed to the decrease in the size of the CPZ under plane stress conditions. The higher AE activity during the substage IIa is attributed to irreversible cyclic plasticity with extensive multiplication and rearrangement of dislocations taking place within the CPZ.

7.0 Acoustic Emission Technique for Monitoring of Forging Processes

AE monitoring of hot forging processes of aluminium alloys has been carried out. With the optimized sensor location at bottom die of the forging press, AE signals generated during open die and closed die forging operations of a number of workpieces of Al alloy were recorded. The results have shown that the forging processes are characterized by three stages: (i) an initial rapid increase in the AE due to generation and movement of dislocations, (ii) a decrease in the AE thereafter and (iii) a significant increase in the AE beyond a specific time due to die filling which promotes increased friction between the die and the workpiece material (Fig.7). Studies carried out on the effect of lubrication during open die forging showed that AE generation increases with decrease in lubrication in the workpiece.

8.0 Summary

Applications of signal analysis on ultrasonic signals for defect detection and microstructural characterization in austenitic and ferritic steels have been discussed. Applications of acoustic emission technique for fatigue crack growth studies in 316 stainless steel and on-line monitoring of forging of Al alloys have also been discussed. These studies point to possibilities of finding robust solutions for characterization of conventional processes and components, based on judicious selection of parameters of the techniques and appropriate signal analysis methodologies.

Acknowledgements

Authors are thankful to many colleagues, specifically Dr. C.K. Mukhopadhyay and Dr. Anish Kumar in the Non Destructive Evaluation Division of Indira Gandhi Centre for Atomic Research for their contributions.

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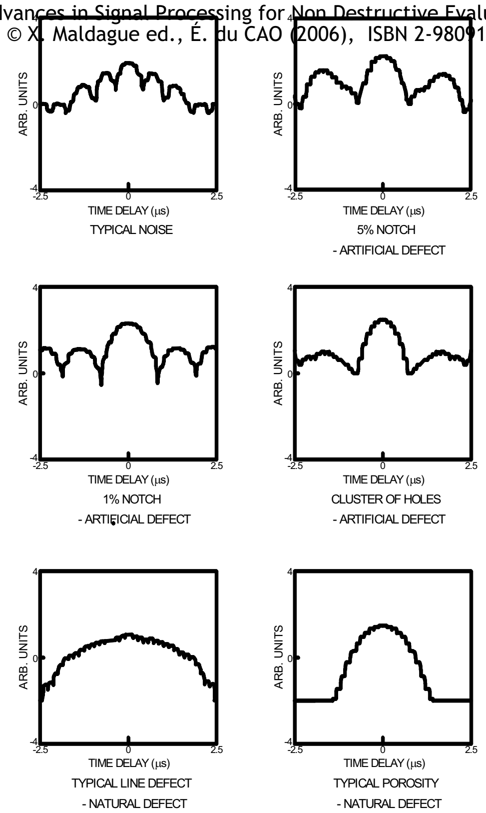

Fig. 1 Ultrasonic signal patterns of typical noise, porosity, notches and cracks in austenitic stainless steel welds.

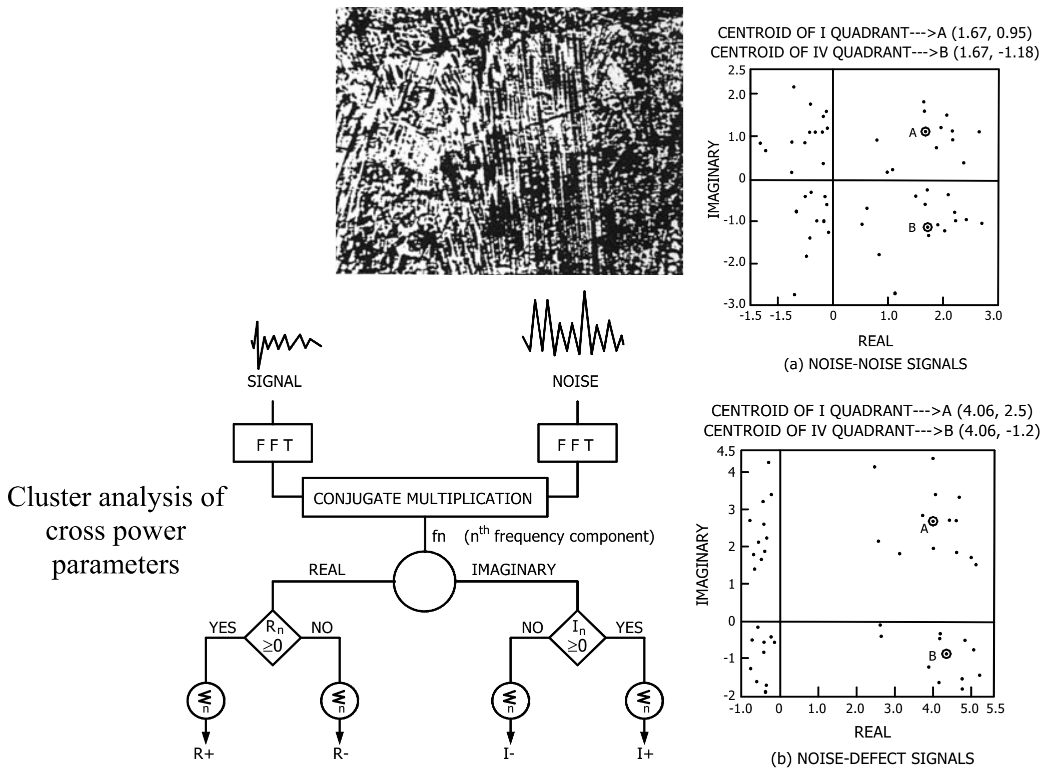

Fig.2 Detection of cracks in Maraging steel weldments

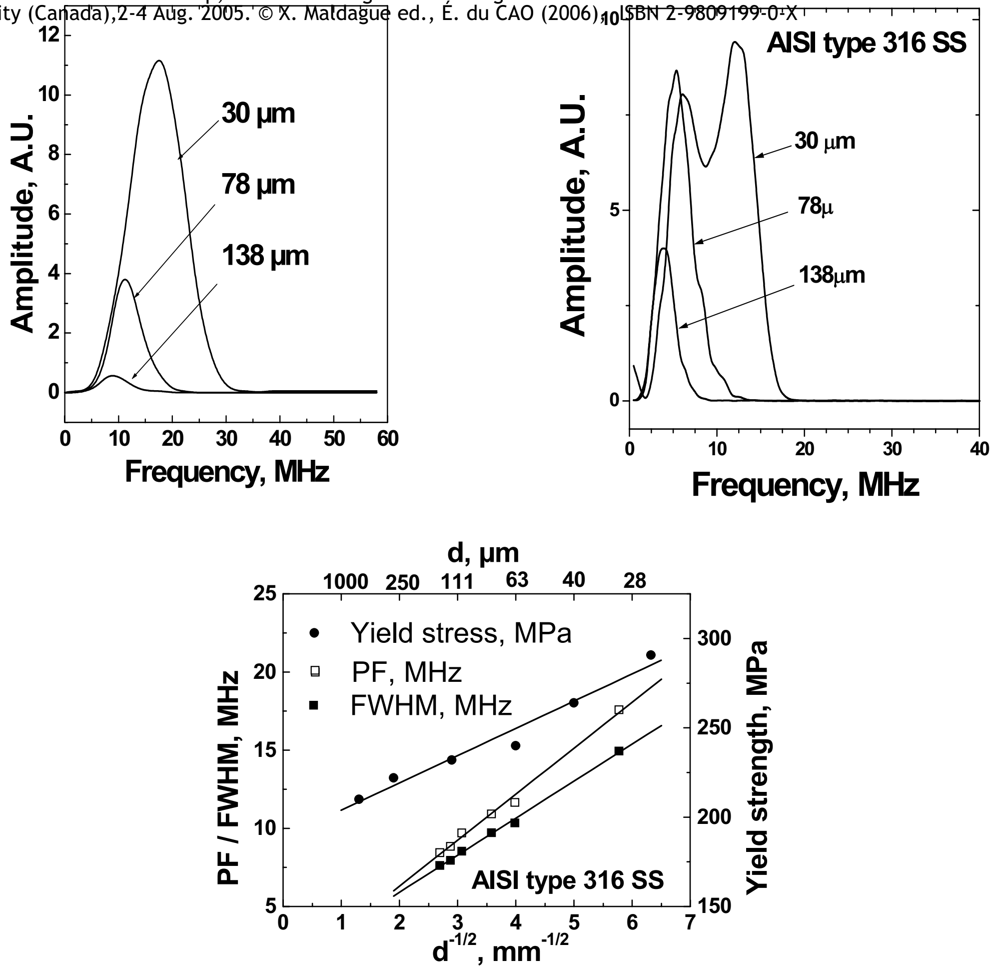

Fig. 3 Grain size measurement in AISI type 316 stainless steel

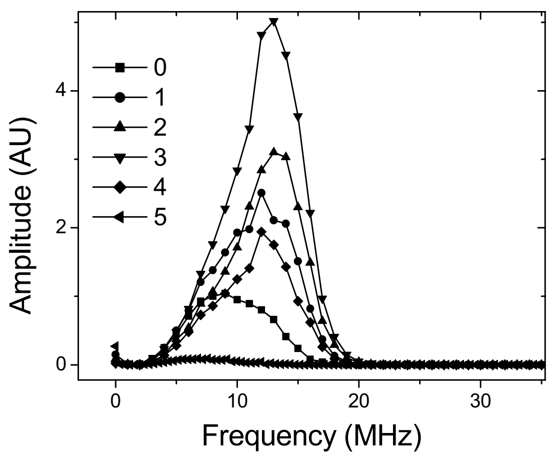

Fig. 4a Autopower spectra of the first back wall echoes obtained in slices 0-5.

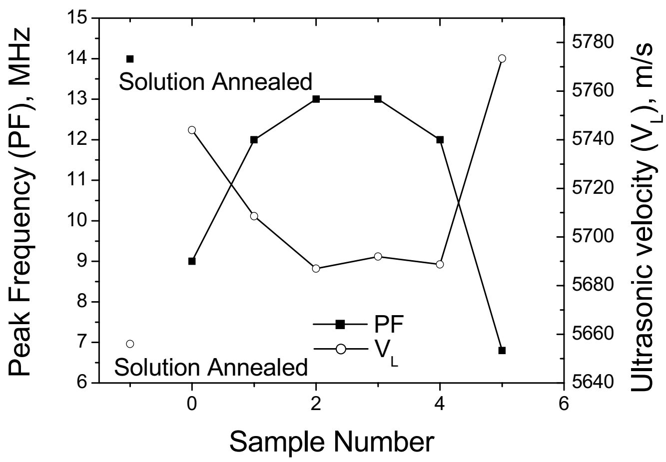

Fig. 4b Peak frequency and Ultrasonic velocity for slices 0-5.

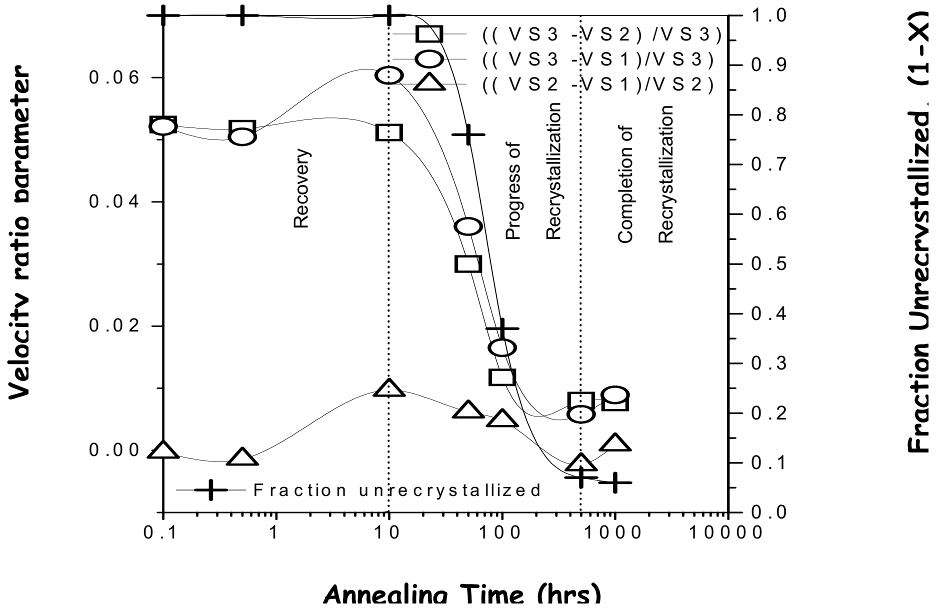

Fig.5. Variation in velocity ratio parameter and fraction recrystallised microstructures with annealing

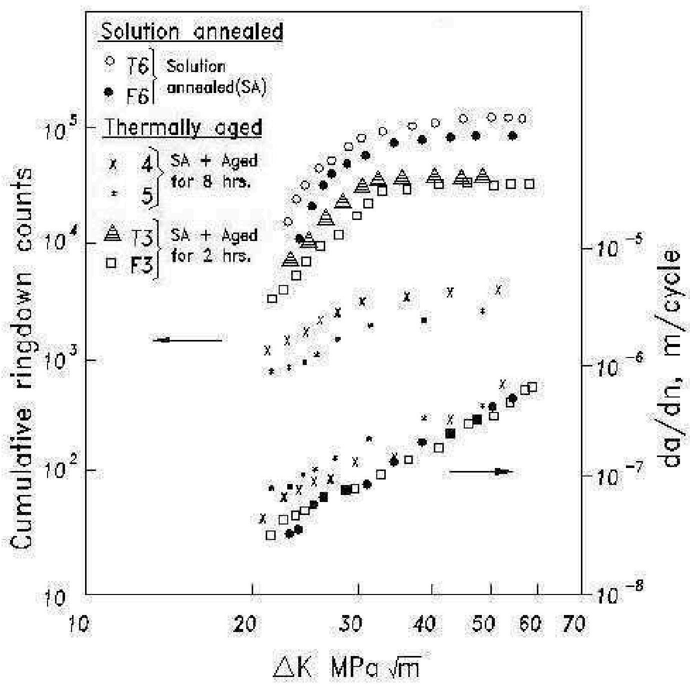

Fig.6. Variation in cumulative ringdown counts (N) and crack growth rate (da/dn) as a function of cyclic stress intensity factor (ΔK) for 25 mm thick solution annealed (SA) and thermally aged (TA) specimens of 316 stainless steel.

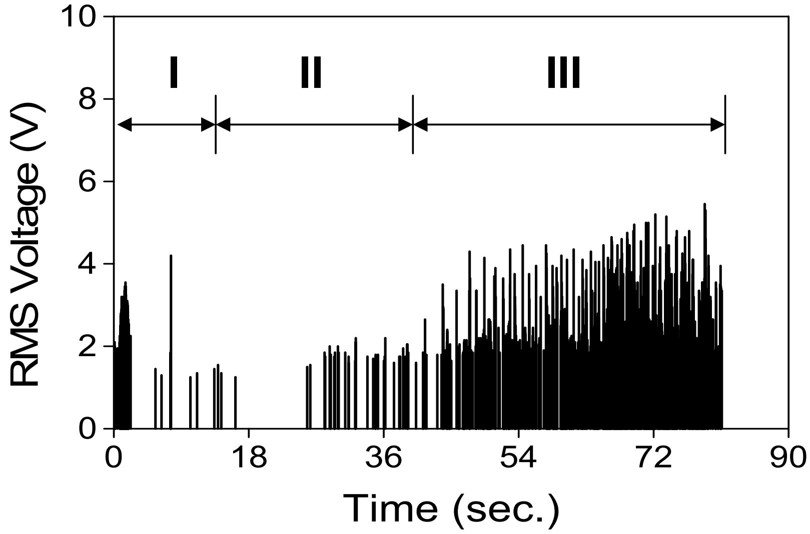

Fig. 7 Acoustic Emission during Open Die Forging of Al Alloy.