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Measurement of elastic modulus and damping properties of friction stir processed pure metals using impulse excitation technique

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The Impulse Excitation Technique (IET) is one of the most reliable and a non-destructive technique to measure dynamic elastic properties of materials i.e. Young's modulus (E), shear modulus (G) and Poisson's ratio (υ). It is also possible to measure damping factor and resonant frequency of materials using this technique. In the current study, IET is used to measure the Young's modulus, natural or resonant frequency (f_r) and damping factor (Q^{-1}) of friction stir processed pure metals with an intention to assess their vibration damping ability. Commercial pure aluminium (Al), copper (Cu) and magnesium (Mg) metals were subjected to single pass friction stir processing employing 600RPM of tool rotational speed and 60mm/min of travel speed. The specimens for IET analysis and for microstructural observations were extracted from the stir zone of friction stir processed plates. The microstructure in the stir zone is severely refined by the friction stirring particularly the grain size of magnesium refined to 25.6μm from its initial size of 780μm. The measured Young's modulus and natural frequency for the processed Al and Cu samples was interestingly lower than their as-received counterpart. But the damping ability of these metals significantly improved after processing. However, for magnesium, the observed trends in the properties before and after processing were quiet opposite to the other two metals. The crystal defects created during the friction stirring could be a reason for the observed trends.

Keywords**:** Impulse excitation technique (IET), resonance frequency and damping factor, friction stir processing.

1. Introduction

Over a decade, the friction stir welding process has been established as a reliable technique to join non-ferrous alloys, particularly, aluminium alloys. Apart from establishing a joint, this process also significantly alters the microstructure of the materials. Friction stir processing (FSP) is a modification of the friction stir welding process has extensively used to alter the surface microstructures of metallic materials [1]. Employing the same process, composite layers have also been prepared by incorporating hard ceramic particles into the surface [2]. The friction stir processed regime, in general, was observed to have a fine microstructure [3] and it is a well-established fact that fine microstructure improves the mechanical properties of metallic materials. These observations have been reported by several researchers [4][5]. But it has to be remembered that the fine microstructure also influences the elastic modulus [6] and damping properties of the materials [7]. The ultrafine microstructures developed by equal channel angular extrusion [8-9] and high-pressure torsion have been observed to exhibit reduced Young's modulus and improved damping properties. Then it is worth to explore such properties of friction stir processed metals and alloys. The present study is an attempt to study Young's modulus and damping properties of friction stir processed commercial pure metals i.e. aluminium, copper, and magnesium. Indeed, there were some efforts in the recent past to determine the damping properties of surface composites fabricated by friction stir processing. Such studies employed dynamic mechanical analyzer for the purpose [10]. However, the present study employs the impulse excitation technique (IET) to measure the damping properties and Young's modulus. The impulse excitation technique (IET) is one of the easy and non-destructive techniques used to determine these properties.

2. Experimentation

Commercially pure metals (aluminium, copper and magnesium) are used in this study. They were cut in to 200 mm × 70 mm × 6 mm samples. A tool made of high speed steel having threaded pin profile was used for the present study. The tool had a shoulder diameter of 15mm, pin diameter of 6 mm and pin length of 4 mm. The FSP was carried out at tool rotational speed = 600rpm; traverse speed=60mm/min and axial force=10kN. These are the optimum process parameters for these metals. Specimens were obtained by cutting the friction stir processed plates at its centre perpendicular to the processing direction. They were polished as per the standard metallographic procedure. The microstructural characterisation of FSPed samples was carried out using an optical microscope and X-ray diffraction (XRD) analysis.

The impulse of a light mechanical impact excites the suspended sample into the resonance frequency. The sample's vibration is collected by a microphone and the signal is processed by a software-based analysis program for the calculation of the resonance frequency, elastic modulus, and damping. For rectangular samples the elastic modulus can be calculated as following formula [11].

$$E = 0.9465\,\frac{m f_f^2}{b}\left(\frac{L^3}{t^3}\right) T_1$$

Where E is the elastic modulus (Pa), f_f is the resonance frequency (Hz), m is the mass of the sample (g), T_1 is the correction factor and L, b and t are the length, width and thickness of the sample (mm)

The damping factor or internal friction (Q^{-1}) can be calculated from

$$Q^{-1} = \frac{K}{\pi f_f}$$

Where K is the exponential decay parameter.

3. Results and discussions

Fig.1 shows decay of sound vibration as a function of time. The time required to decay the sound vibration represents the damping ability of the material. If the amplitude of vibration decays quickly then it has better damping properties. It is evident from the fig.1 that the time for decaying the vibration reduced in the case of friction stir processed aluminium and copper. Whereas, it takes more time to decay the vibration in case of processed magnesium. The damping factor (Q^{-1}) as calculated from these curves are shown in fig. 2. It is implied from the figure that damping factor increased after processing for aluminium and copper. Indeed for copper, the damping factor doubled after FSP whereas for aluminium the improvement in damping factor is marginal. However, the damping factor for magnesium considerably decreased after FSP. The elastic modulus of copper and aluminium, in general, decreased after processing. However, for magnesium it is unchanged.

The observed changes in damping factor and elastic modulus might have been due to the microstructural changes occurred during FSP. Hence, microstructural investigation was carried out to explain the observations. Fig. 3 shows the optical micrographs of the base metals and the FSPed metals. In each sample, stir zone can be clearly distinguished from the base metals. The stir zone of this samples consists of equi-axed grains, the grain size is finer in the stir zone than in the base metals. The variation of the grain size before and after FSP is shown in Table .1.

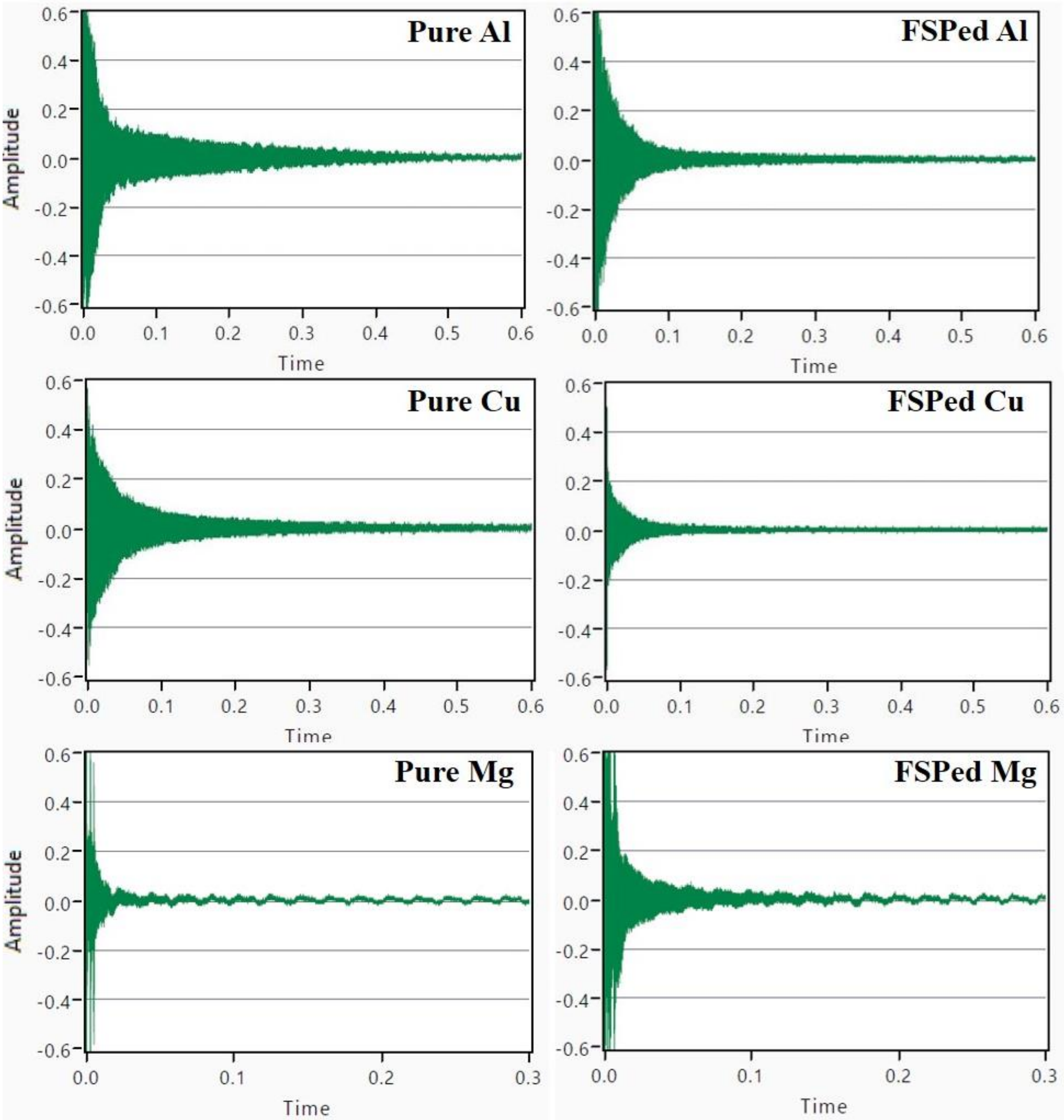

Fig.1 Decay of sound vibration as a function of time for materials before and after FSP

X-ray diffraction patterns (not shown here) of base and processed metals were obtained to calculate the density of dislocations. It was observed that dislocation density decreased after processing in copper and in aluminium whereas in magnesium it is increased after processing. The aluminium and copper plates used in this study was received in rolled condition and it is expected to have high dislocation density. But after FSP, the dislocation density was low because the microstructures are fully recovered and recrystallized by thermo-mechanical cycles during FSP. Whereas magnesium was received in as-cast condition. As-cast ingots expected to have only equilibrium number of dislocations. Hence, the number of dislocations increases after processing in case of magnesium.

The defects, i.e. dislocations, grain boundaries, present in the material helps to improve the inherent damping factor of them [12]. The decrease in grain size implies that increase in grain boundary area

[13]. This was believed to be responsible for the improvement of damping properties in aluminium and in copper. Whereas in case of magnesium, increase grain boundary and dislocations leads to the formation of dislocation tangles thus led to poor damping. A decrease in damping was reported for ECAE processed pure magnesium supports the present observation [8].

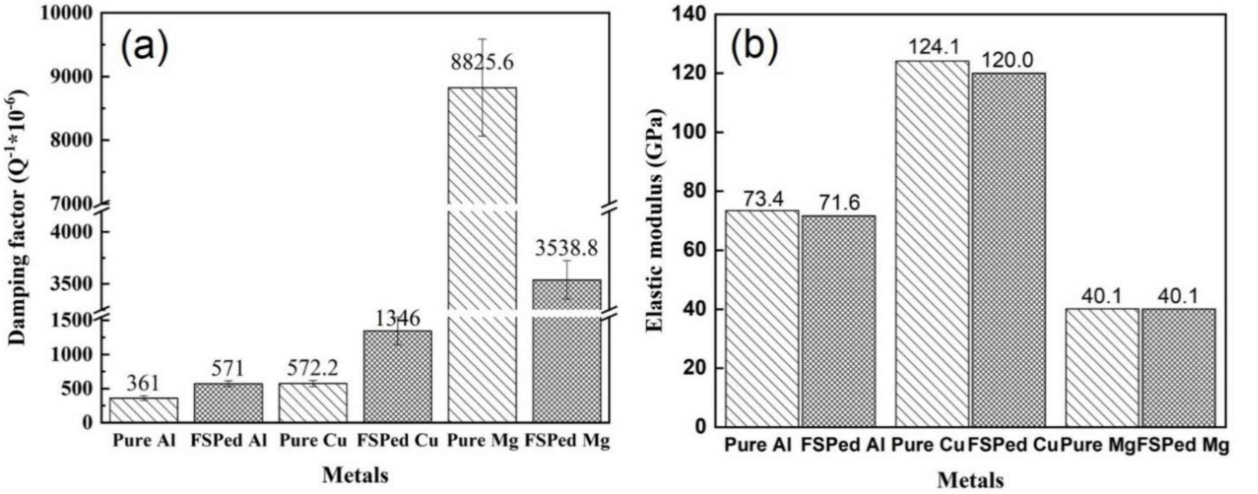

Fig. 2 (a) Damping factors and (b) elastic modulus of pure metals before and after FSP

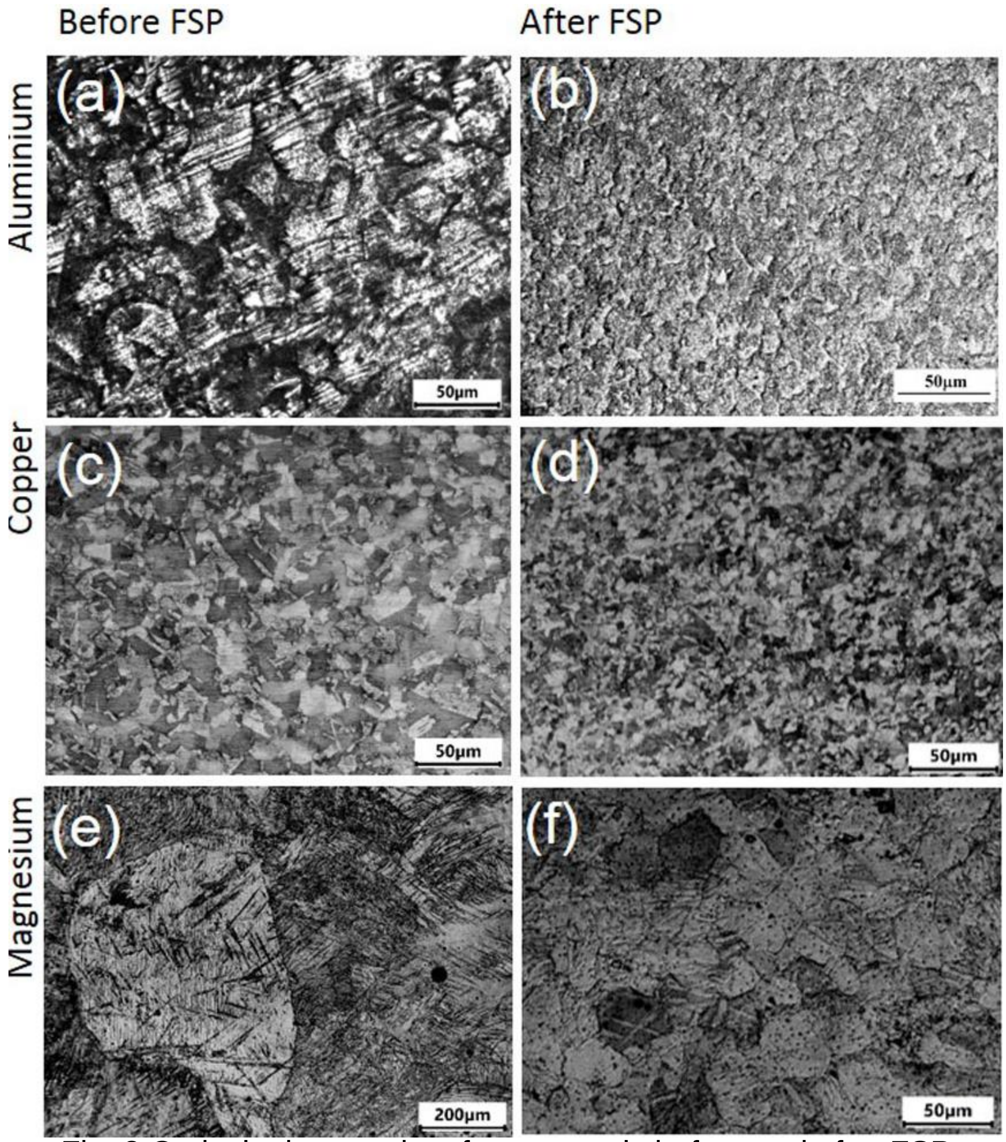

Fig. 3 Optical micrographs of pure metals before and after FSP

Table 1 Calculated values of average grain size and dislocation density before and after FSP

S. No.	Material	Grain size, μm		Dislocation density (ρ) $\times 10^{12}/m^2$		
		Before FSP	After FSP	Before FSP	After FSP	%Change
1	Aluminium (Al)	44	10	4.24	2.57	−39.3
2	Copper (Cu)	20	4	1.49	0.84	−43.6
3	Magnesium (Mg)	780	26	1.67	2.99	+79.0

The creation of defects particularly an increase in grain boundary area led to decrease in density. This results in the decrease of elastic modulus of aluminium and copper. It has been observed that materials exhibit reduced elastic modulus after being subjected to severe plastic deformation [9].

Conclusion

1. Commercial pure aluminium, copper, and magnesium metals were friction stir processed without leading to defect formation.
2. The elastic modulus and damping properties of friction stir processed metals were measured using the impulse excitation technique.
3. The damping factor was increased after processing for aluminium (+58%) and copper (+135%) due to an increase in the grain boundary area.
4. The damping factor of magnesium decreased (−60%) owing to an increase in dislocation density after processing.
5. The elastic modulus of aluminium and copper was marginally decreased after processing.

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