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Effect of Friction Stir Processing on AZ91 Mg-alloy: A Review

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ABSTRACT

Generally properties of as-cast AZ91 soft Mg-alloy can be improved by conventional artificial aging. Conventional methods are time consuming and expensive process. Friction stir processing (FSP) based on working principle of Friction stir welding can replace the conventional processes at some extent. FSP generates enough heat in process to decrease grain size of coarse grains significantly and accordingly alter the properties. FSP extensive used for modification of morphology, grain refinement etc. and especially for as cast alloys. By performing FSP successfully on AZ91 alloy many properties of as-cast AZ91 can be changed significantly by varying friction stir process parameters. The improved resultant properties of Friction stir processed AZ91 alloys are credited to plastic deformation of alloy sheet by rotating non-consumable tool. Due to plastic deformation number of dislocation increase and it may by pile up, as a result the movement of dislocations are restricted and it required more stress to deform, thus strengthen the alloy. Tool in FSP plays crucial role, as tool shoulder and tool pin generate frictional heat, tool pin also used to improve material flow characteristics. FSP reduced grain size and enhanced various properties. This paper mainly reviews the effect of FSP on AZ91 Mg-alloy in terms of various properties enhancement.

Keywords: Friction stir processing; Plastic deformation; AZ91 Mg-alloy

INTRODUCTION

Mg alloys has low density, good conductivity, good damping characteristics with enough specific strength and it is one of the lightest metals used in various applications like automobile and aerospace industries, although the uses of Mg alloys are restricted because of limited number of independent slip systems in hexagonal close packed (HCP) structure, due to that, ductility and formability is also limited. Properties of this kind of alloys can be improved by techniques like age hardening, and strain hardening. Generally, Mg alloy can be categorized in two types Mg-Al-Zn and Mg-Al-Mn alloys for strength and ductility at room temperature. As cast AZ mg alloys with higher aluminum content such as AZ91 has course network like grain boundary phase β (Mg17Al12) with high cast-ability. Main alloying elements of AZ91 Mg-alloy are 9 wt% aluminum, and 1 wt% zinc. Microstructure of AZ91 alloy characterized by Mg- β (Mg17Al12) eutectic at the grain boundaries with alpha magnesium matrix. This compound has poor metallurgical stability and creep resistance of alloy at high temperatures, because β (Mg17Al12) compound has low melting point, it is incoherent with mg matrix. During FSP, enough heat generated but it not sufficient to soften material as result re-crystallization of course grains take place and decreasing grain size significantly and changed its properties [1-7]. FSP based on plastic working procedure that`s why now a days it used extensively. FSP extensive used for modification of morphology, grain refinement etc. and especially for as cast alloys [8]. After FSP on AZ91 grain size decreased from 100 um to 15 um as a result hardness also increase from 70 HV to 75 HV in case of single pass, on double pass hardness increases from 70 HV to 98 HV [9]. Generally, FSP performed to improve cast-structure, grain refinement, replace convention processes, to prepare surface metal matrix composites, etc. [10].

In FSP a rotating tool penetrate in plate of AZ91 called plunging and tool moves in plate at certain direction with certain transverse speed as result highly plastically deformed zone produced due to associated stirring action [11]. Improvement in properties, morphologies are highly sensitive to process parameter like plunging force and time, tilt angle, rotational and transverse speed, profile of pin and etc., because all these parameters are affected to the heat generation. FSP is inexpensive, controllable, reliable and less time consuming for grain refined compare to other techniques [12]. Grains refined from courser to 8.3 um, 5.8 um respectively for 1 pass and double pass respectively, as results hardness increase 78.2, 81.2 for single pass and double pass [13]. The parameters of the FSP are highly responsible for extent of modification of the properties of alloy. Generally used in the range from 400 to 1500 rpm, transverse speed from 30 to 52 mm/min with certain tilt angle, downward force and plunge depth [14]. Fatigue strength and crack growth rate can be improved by FSP while in conventional artificial aging it is not observed [15]. Variation of properties is because of microstructure, so microstructure and its features are plays importance role in changed properties [16]. Some time with FSP used a particles like carbide or titanium carbide with intense to increase strength of magnesium-alloy, as result combine effect of plastic work and particles make surface composite in magnesium-alloy and many a properties of alloy can changed.

In literature it is proven that by surface composite hardness of AZ91 increase from 70 VHN to 146 VHN [17]. Grain size also decreased in FSP and friction stir welding (FSW) [18-20]. This paper review effect of FSP on AZ91 Mg-alloy. To improved mechanical properties like strength, ductility, it is necessary to modify the distribution and morphology of β ($Mg_{17}Al_{12}$) inter-metallic. Two methods are mostly used to serve this purposes heat-treatment and plastic working or strain hardening mechanism, heat-treatment (artificial hardening) are time consuming as well as not cost effective [21]. In submerged friction stir process high cooling rate can be achieved 13°C/S, which restrict grain growth and gives very fine grains with grain size 1.2 um [22]. FSP has also potential to produce surface metal matrix composite (SMMC) via FSP by dispersing particles like SiC, Al_2o_3 as reinforcement for enhanced properties of material, by using TiC particles in nano dimensions metal matrix nano composite can be produced via FSP which improved wear resistance of material and B_4C particles are also used for enhanced wear resistance by producing SMMC via FSP, for uniform distribution of these reinforcement particles and increase the efficiently of FSP now a day new technique are used friction stir vibration processing (FSVP) to avoid agglomeration of particles during FSP, in which material vibrating in normal to processing direction, which gives uniform properties distribution in material [23-30]. By addition of nano Al_2O_3 particles during FSP and formation of a composite layer refined the structure and increased the hardness by almost more than 30%, friction stir processing of AZ91 with alumina particles also increases the wear resistance significantly by forming metal matrix nano composite [31-37]. FSP is also used to develop hybrid surface composites by using of more than one reinforcement [38-51]. This paper mainly review the effect of FSP on AZ91 Mg-alloy.

EFFECT OF FSP ON AZ91 MG-ALLOY MICROSTRUCTURE

AZ91 subjected to FSP procedure: single pass with Normal Friction Stir Processing (NFSP) and Submerged Friction Stir Processing (SFSP), because of the rapid solidification rate grains are refined effectively, the microstructure evolution responsible for enhanced mechanical properties of AZ91 with various FSP procedures with prime objective to identify the optimized FSP procedure for AZ series mg-alloy modification, Figure 1 indicated evolution of microstructure and grain size via FSP in terms of comparison with As-cast structure [8].

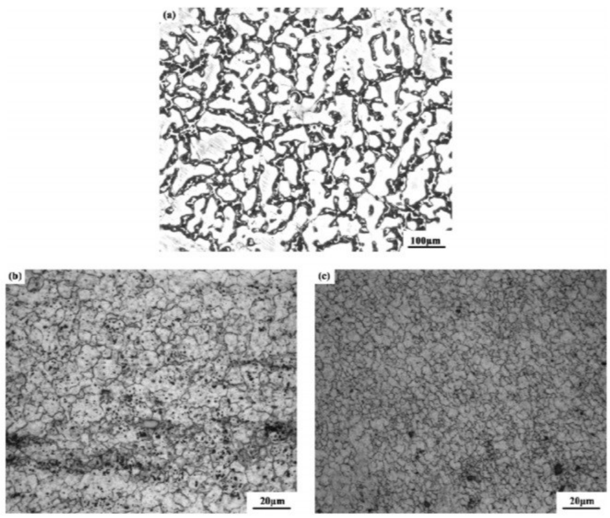

FIGURE 1. Microstructure of (a) Base metal, (b) Normal friction stir processed AZ91 alloy, (c) Submerged friction stir processed AZ91 Mg-alloy [8]

In as cast structure of AZ91 observed course eutectic of secondary phase B-$Mg_{17}Al_{12}$ at grain boundary of matrix alpha magnesium as shown in Figure 1(a). Due to stirring action the secondary particles are dissolved in matrix as result grains are refined as shown in Figure 1(b). Due to higher heat extraction rate or high solidification rate restrict the grain growth as result grains are refined at great extent in Submerge friction stir processing as shown in Figure 1(c). As the grain size decreased strength, hardness, toughness increased.

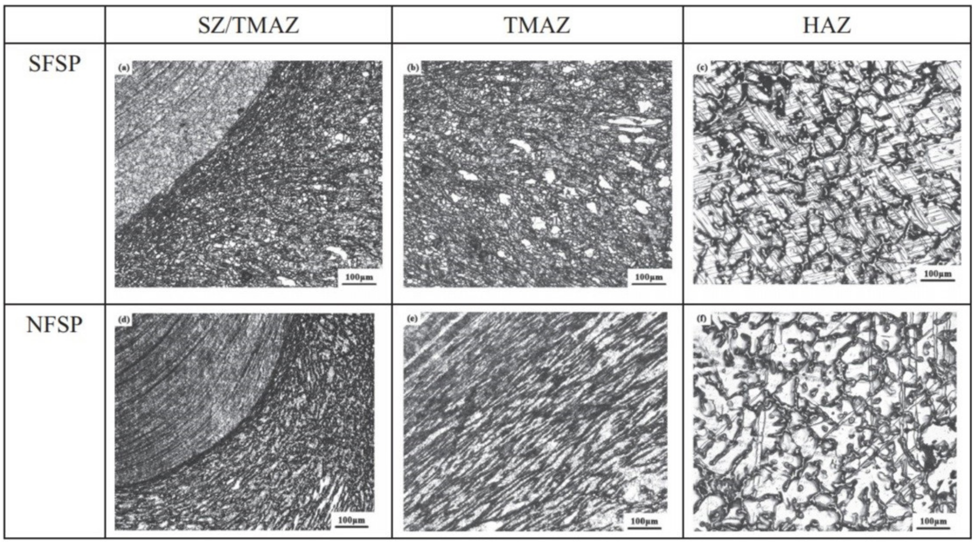

FIGURE 2. Microstructures of submerged friction stir processed and normal friction stir processed AZ91 Mg-alloy with different zone a, d) at interface between stirring zone and thermo-mechanically affected zone b, e) Thermo-mechanically affected zone c, f) Heat affected zone [8].

In Figure 2 it can be observed that away from stirring zone (SZ) effect of grain refinement reduced and as result hardness distribution and other properties like tensile changed with that in normal friction stir processing (NFSP) and submerge friction stir processing (SFSP). SFSP is done with cooling media like air and water to increase rate of heat extraction during FSP to modified microstructure significantly. AZ91 also a suitable material for FSP without any additional of powder like alumina powder. In NFSP rate of heat extraction is less, so as result grains refined and dissolution of secondary particles high in SFSP compare to NFSP. Compared with NFSP, SFSP has remarkable grain refinement effect, the average grain size of the NFSP and SFSP specimen is 8.4 ± 1.3 and 2.8 ± 0.8 um respectively [8]. Furthermore, the microstructures in the Thermo-mechanically affected zone (TMAZ) and heat affected zone (HAZ) for the SFSP are much finer than those for the NFSP, based on that improvements tensile properties and toughness also changed. In base metal (BM) tensile properties are not good because of course network of secondary particles, by FSP all tensile properties improved by strength hardening in both NFSP and SFSP [1, 2, 8].

EFFECT OF FSP ON AZ91 MG-ALLOY MECHANICAL PROPERTIES

Properties are improvement are depend on FSP parameters and it's can observed by performed FSP on AZ91 alloy with different parameters indicated variation in properties due to variation in FSP process parameters [13]. Figure 3 indicated properties improve with number of pass and also FSP replaced conventional method for strengthening of material.

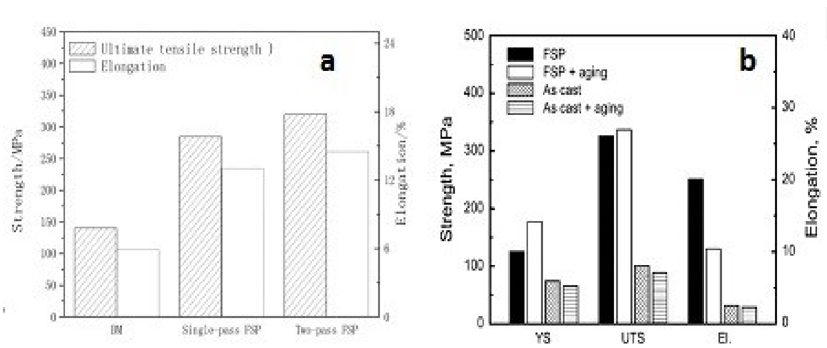

FIGURE 3: (a) Tensile properties comparison of base metal, single pass and two pass FSP of AZ91[13], (b) Effect of FSP and aging on tensile properties of AZ91 [13].

As per the Figure 3 (a) it can be observed that before FSP, the tensile properties of as cast AZ91 Mg-alloy are poor, due to course network of secondary particles at grain boundary of matrix of AZ91, so this course network like particles are responsible for these poor properties of AZ91 as cast mg-alloy, as per Figure 3 (a) UTS of base metal is around 148 MPa after performed FSP on base metal UTS of FSPed AZ91 increased significantly around 260 MPa and further increased after performed FSP with double pass around 325 MPa [13]. After FSP, due to distraction and dissolution of B-Mg17Al12 phase in matrix, grains refined effectively and gives a excellence change in properties, and due to high stirring action in double pass of AZ91, properties are improved further. Figure 3(b) gives an idea about properties evolution with various processes, there is no significant change in properties of as cast and as cast + aging, tensile properties are similar for both as cast and as cast + again no significant improvement observed. After performed FSP successfully in increased significantly compare to as cast [13]. To observed effect of FSP parameters on AZ91 in terms of properties there is a investigation was done, as per that research to optimize properties by FSP, out of other transverse speed best suited speed was 30 mm/min with variation of rotational speed as shown in Figure 4 [14].

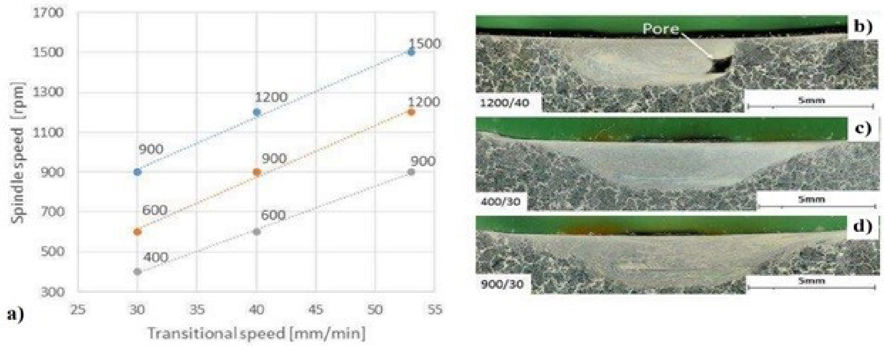

FIGURE 4. Variation in parameters in FSP and macrostructure at various parameters [14]

For observation of microstructure it can divided in three zone: 1) Stirred zone 2) Thermo-mechanically affected zone, 3) Heat affected zone 4) Interfaces between all these zones. As per parameters of FSP and number of pass distribution of hardness changed, so this kind of hardness distribution inspected by experimental study by researcher as shown in Figure 5 [22].

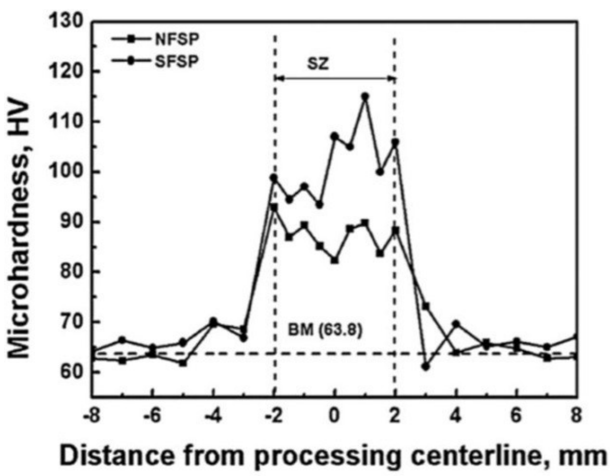

FIGURE 5. Micro hardness distribution of the samples [22].

Hardness distribution of different zone depends on grain size of different zone in material so it affected by microstructure of these zone, as shown in Figure 5, base metal hardness found 63.8 HV in as-cast condition, after performed NFSP on it hardness increased from 63.8 HV to around 92 HV of Stirring zone due to the grain refinement, in SFSP grain size reduced effectively because it didn't allows to grain growth because of high cooling that's why hardness increased from 63.8 to around 118 HV of stirring zone. Based on harnesses distribution tensile properties and fracture behavior of material is also improved significantly as shown in Figure 6 [13].

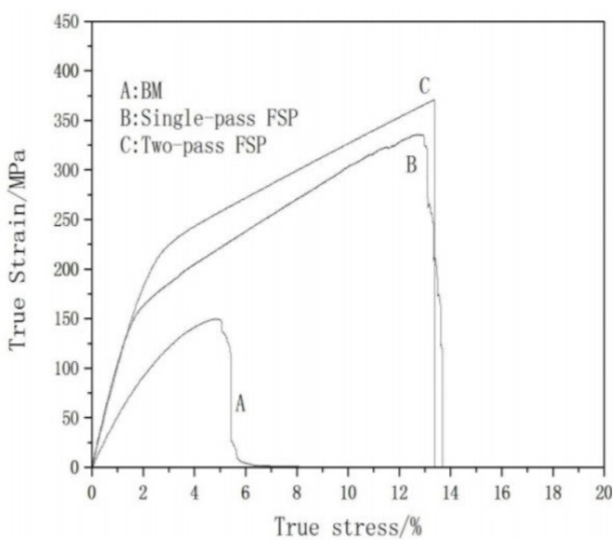

FIGURE 6. Stress Strain diagram of AZ91 with different number of FSP passes [13].

Coarse network of eutectic B-Mg17Al12 compound broken into small particles and it dissolved in to matrix of magnesium, in the experimental studied it proven that average grain size can be refined from coarse grain to 8.5 um in single pass. Dissolution of B-Mg17Al12 can be observed by studied of XRD of AZ91 alloy as shown in Figure 7 [13].

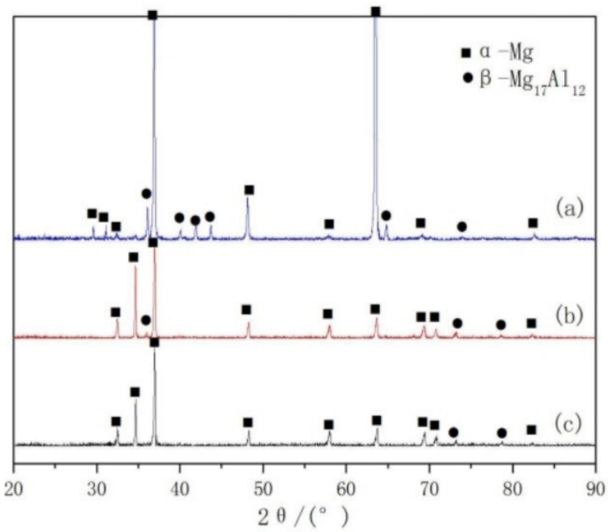

FIGURE 7. XRD of AZ91 a) BM, b) Single pass, c) Double pass [13].

X-Ray Diffraction is used for identify the intensity of secondary particles in magnesium matrix before FSP and after FSP, as show in Figure 7 compare to base metal number of peaks decreased after FSP due to break up of secondary particles network and intensity of these particles decreased further in double pass FSP that's why number of peaks are very less, basic principal behind the FSP is strain hardening and modified morphology of as cast structure by dissolution of secondary parties B-MG17AL12 and to ensure that XRD technic was used. After FSP it can be seen that number of different peaks are decreased of B-MG17AL12 compare to BM because during FSP a coarse network of B-MG17AL12 break in to small particles and dissolved in to matrix of Mg [9, 13]. Fatigue behavior also improved significantly by FSP and study has been done on this property, based on that fatigue life increase if AZ91 by FSP compare to as-cast and heat treatment material because inclusions and defects like casting and forging defects can be reduced and eliminated significantly as result fatigue strength is increase. As shown in Figure 8 enough improvement can be observed by FSP compare to As-cast and Heat treated sample at same stress amplitude. As result decrease crack growth rate [15].

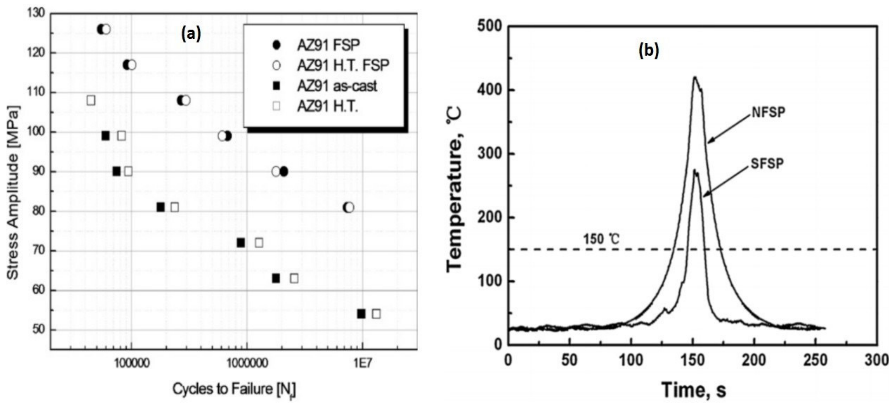

FIGURE 8. (a) Fatigue properties AZ91 in as cast [15], FSP and HT condition, (b) Temperature profile during NFSP and SFSP [22].

As per Figure 8 (a), FSP AZ91 survive with higher stress amplitude as well as with high number of cycle to failure, and as discussed heat extraction rate or solidification rate are prohibited grain growth and Figure 8 (b) indicated the temperature profile of FSP in air (NFSP) and under water or quickly quench (SFSP). Pack temperature reach in NFSP around 400°C at certain time ~ 150 second and at high temperature grain growth rate is more dominant compare to nucleation rate so it allow to grow the grain size, but in SFSP due to high heat extraction rate peak temperature reached only ~ 270°c, so it is quite low compare to 400°C, so such lower temperature nucleation rate is more dominant so it doesn't allow further growth and grains refined significantly [15].

TABLE 1. Prominent results of FSP on AZ91

Reference	Method	Prominent Results
[1]	Additional of rare earth element in AZ91	Increased strength and ductility at high temperature.
[2]	Rapid Deformation	Improved creep resistance and micro hardness 23% from base metal
[8]	SFSP	Compare to NFSP grains refined furthermore with grain size (~ 2.8)
[9]	FSP	Enhanced tensile properties by severe plastic deformation and dissolution of secondary particles

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[10]	FSP	Compare to base metal and artificial aging tensile properties increased
[11]	FSP	Exhibit good ductility and strength at high temperature
[12]	FSP	Effective grain refined as result properties improved
[13]	FSP	Increase micro hardness by SPD and it achieved up to 81 HV
[14]	FSP	Optimized parameters for AZ91 which is 900/30 mm/ min, as rotation speed increase average grain size decreased
[15]	FSP	Increase fatigue strength at room temperature
[16]	FSP	Machinability not affected by alter the microstructure but properties are improved
[17]	FSP	Improved mechanical properties by produced surface composite by FSP of AZ91 with titanium carbide

SUMMARY

FSP is the potential technique to replace conventional processes for strengthening the material and also a cost effective process because the diffusion rate of the conventional processes is very slow compare to FSP. FSP created heat as result heat generated and diffusion of secondary particles take place and morphology changed, so by this way morphology of AZ91 changed by FSP and because of that grain size reduced significantly via NFSP or SFSP because of that properties like UTS, YS, Elongation, hardness, toughness enhanced. Temperature is also high ~ 180°C to 350°C in NFSP for reduced Temperature used SFSP but the rate of dissolution of secondary particles may be high in NFSP, but solidification rate is also high in SFSP as result grain are further refined by SFSP. Because of such high temperature sufficient heat generated as result material flow inside the sample plate increase and numbers of new strong bonds are created between particles because of that material properties are vary with that. Process parameters in FSP are very sensitive to change in properties. Table 1 shows prominent results of FSP on AZ91.

Friction stir process is an effective surface modification tool, which improves surface properties of specimens. The AZ91 has poor mechanical properties in as-cast condition and most of those can be enhanced significantly via FSP. Because of stirring action many bonds are broken and new bonds are form so due to that wear resistance of AZ91 mg-alloy change, so by perform FSP successfully on AZ91 wear resistance can be improved. More efforts required by processing community, so that FSP can be used for industrial applications.

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DECLARATION OF COMPETING INTEREST

None

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