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Review

Review of Friction Stir Processing (FSP) Parameters and Materials for Surface Composites

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A B S T R A C T

This paper presents a review of important aspects related to the Friction Stir Welding and Friction Stir Processing (FSW/FSP) concepts. The FSP, as a variation of the FSW, uses the same principle, but instead of the material joining, the FSP focuses on a surface modification aiming at improving surface properties of the substrate material. Thin surface composites can be made either by using grooves or drilled holes.

FSP process parameters have been elaborated: axial force, rotational and traverse speed, tilt angle, insertion depth and tool geometry, as well as number of passes. Review of the used materials in fabrication of composites by using FSP is shortly presented. Effects of the FSP on mechanical properties have been discussed: effects on the microstructure, hardness and wear properties, tensile strength, and fracture and defects formation. FSP has evolved as an efficient method to modify surface structures, especially important for metallic materials that exposed to different harsh conditions, and further research will enable its wider use in industry.

1. INTRODUCTION

Metal alloys have found a wide area of use in industry in different components and structures. They are widespread in almost all industries, including railway, airline, space and automotive. Metal alloys are perfectly suited for the balance between cost, weight and mechanical properties that can be optimized by appropriate material selection and processing routes. One way to improve mechanical properties of the metal components is to modify their surfaces, such as by reinforcing the matrix material with particles or fibers that can vary in size and composition, thus forming a composite material within thin surface layers. Several fabrication methods are already established like plasma spraying, laser melting, cold spraying etc. [1,2]. However, these techniques still exhibit certain flaws and drawbacks, such as the need for the thermal treatment or some other postprocessing, low efficiency, high-cost equipment, or nonuniform alloying element distribution, or formation of unwanted phases [2].

The Friction Stir Processing (FSP) is a relatively new technology with main advantage of processing temperatures below the melting temperature of the substrate materials [1,3]. FSP is a variation of the Friction Stir Welding (FSW). FSW realises material joining, whereas FSP is used to locally modify the substrate material in order to fulfil the need for specific properties. FSP is a solid – state process that provides structural homogeneity, strengthening and grain refinement without changing geometry of the processed material [1]. It has been used to remove surface defects like cracks and pores and to improve mechanical and tribological properties of processed material [4].

2. FRICTION STIR WELDING AND FRICTION STIR PROCESSING (FSW/FSP) CONCEPT

In general, Friction Stir Welding (FSW) realises insertion of the rotary tool of specific profile [5] into the interface between two workpieces, under axial force, and then moving it along the welding line [6]. FSP has similar concept to the FSW, but it realises processing of only one workpiece within a surface zone. The tool consists of a pin (used for plunging into a specimen) and a shoulder (Figure 1a), of various shapes and dimensions, as can be seen in literature [7]. Heat is generated in contacts between the tool and workpiece, inducing deformations and material stirring, thus forming solid weld (in FSW) or modified material with a surface layer (in FSP). The tool has two primary functions: heating (by friction generated by the tool shoulder), and substrate material changes by stirring [2].

The Friction Stir Processing (FSP), as a variation of the FSW, uses the same principle, but instead of the material joining, the FSP focuses on a surface modification aiming at improving surface properties of the substrate material. Both FSW and FSP processes can be optimized by varying process parameters aiming at improved quality of the final component [1]. The processing involves three types of motion: plunge and dwell, traverse and retract. Phase one starts with setting up of the optimal rotational speed with vertical tool motion towards specimen. When rotational speed is set the pin plunging into material can begin until the tool shoulder comes in a contact with material, where heat generation increases as plunging intensifies. The friction between the tool and specimen, together with the plastic deformation, generates heat that softens the material enabling the tool to penetrate the material without melting it [3]. The penetration proceeds until the shoulder gets in a contact with specimen, when the dwelling stage starts (Figure 1b). Here the tool, rotating, remains in its previous position for some predefined time, warming up and softening the material.

In the second phase, the translational motion along the processing direction is realised, where the highest heat generation is at the front of the pin, because of its contact with a material of a lower temperature. The softened material is forced to flow around tool and is mixed in this way. The mixing in this phase is not symmetric. Therefore, sides of the processed zone are being named according to the material flow directions, as advancing and retreating side. The advancing side (AS) is the side where rotational direction (in terms of tangential velocity vector) and translational tool directions are the same, and retreating side (RS) is the side where tangential velocity vector is opposed to the processing direction (Figure 1a,b) [3].

At the end of the second phase, translational motion stops, with rotational motion still present (Figure 1c). During the third and final phase, the tool is retracted from the welded material leaving the exit hole behind it (Figure 1d). After the mixing, the FSP zone is cooled, and a defect-free stirred zone is formed. However, unlike at the FSW process where it is not common, FSP can involve the flat tool without the pin that penetrates the surface. Flat tool without a pin (pin-less tool) is especially investigated for the fabrication of thin composite layers on the substrate surface.

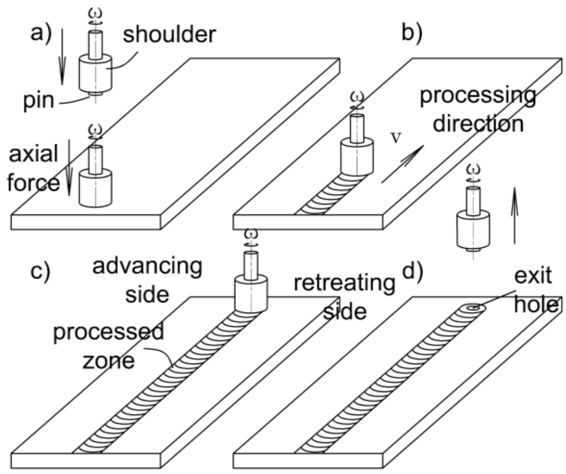

Fig. 1. FSP working principle.

2.1 FSP surface composites fabrication

In order to create the surface composites by FSP method, two approaches are commonly used: by grooves, or by drilled holes [2]. The grooves or holes are machined on the surface, and further filled with a reinforcement particles, as shown in Figure 2 [8–20]. There are several approaches that can be used, but the widely investigated one is to start with FSP with pin-less tool over these filled grooves, followed by the repeated FSP by using the tool with a pin to homogenously distribute reinforcements. The groove dimension and geometry can be varied depending on the material requirements. Also, the number of grooves on surface depends of the composite design (e.g., volume fractions).

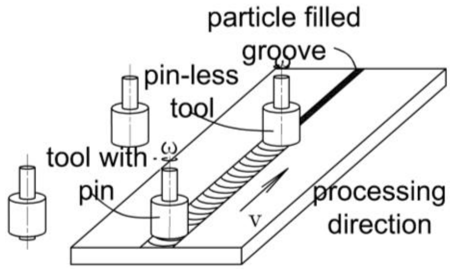

Fig. 2. Groove method for composite fabrication.

Second FSP method for surface composites fabrication does not need the pin-less tool like the groove method. This method consists of drilling consecutive blind holes on the material surface which are filled with the reinforcement particles [21,22] (Figure 3). Now the FSP can be processed directly on material, without any pre-processing using pin-less tool, as tool shoulder acts as a sealant which prevents particle loss [2].

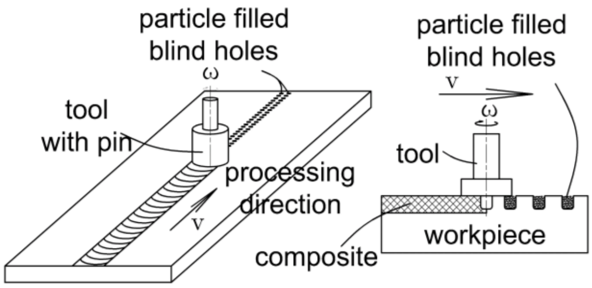

Fig. 3. Hole drilling method for composite fabrication (left) and cross section (right).

Different approaches have been investigated [2,23], that use the same hole drilling technique but with introducing a thin sheet cover over the drilled holes or groove in order to prevent reinforcement particles from ejecting.

There are also studies that used hollow, pin-less tool filled with particles which enables mixing of the substrate material with particles during the FSP [2]. Combination of compocasting method of composite fabrication (mixing melted substrate material with reinforcement) and post-processing by FSP has been also studied [24,25].

3. FSP PROCESS PARAMETERS

The most influential parameters affecting the FSW/FSP with the highest impact on heat input, material flow, heat generation, peak temperature and final surface quality, are: traverse speed, rotation speed, axial force and tilt angle [26].

The largest part of a generated heat during FSW/FSP is a product of friction between the tool and workpiece material, which is directly dependent of area and pressure at the tool shoulder - surface interface, and this interface is controlled by the axial force. The material around the pin is locally heated and subsequently softened which enable that it moves around the pin, due to the rotational and translational motion of the tool. Beside friction generated heat, heat is also created by severe plastic deformation of the material [3]. It is proven that axial force increases heat generation, reduces isotherms density and expands Heat Affected Zone (HAZ) [27].

3.1 Axial force

Axial force is the force given via the tool to a workpiece in downward direction [4]. Increasing axial force directly affects the surface quality – improving hardness and increased mechanical properties at stirred zone [26]. Important factor regarding axial force is its consistency in order to produce good microstructure quality, therefore force control is of the utmost importance [27].

3.2 Rotational and Traverse speed

Rotational speed (ω) measured in rotations per minute (rpm) in clockwise or counter – clockwise directions, depending on the tool geometry, as well as traverse speed, or translational speed (v), measured in millimetres per minute (mm/min) are the most significant parameters of FSW/FSP process, because they significantly affect stirring of material. Material stirring begins with rotating action of the tool, proceeds with both rotational and translational, and finishes with pure rotational movement of the tool which doesn't end as long as tool and specimen are in contact [5]. It is proven that with increase of the rotational speed, the generated temperature increases significantly [28–30]. When rotational speed is of some constant value, the average welding temperature is increased when translational speed is decreased [31]. Elangovan et al. [32] tested speeds of 0.37; 0.76; 1.25 mm/s, with rotational speed fixed at 1600 rpm, and concluded that the best tensile properties are achieved at speed of 0.76 mm/s. Dinaharan et al. [12] tested various rotational (800, 1000, 1200, 1400 and 1600 rpm) and traverse (20, 40, 60, 80 and 100 mm/min) speeds in surface composites fabrication by FSP and concluded that cross-sectional stirred zone area increased with increasing the rotational speed (for fixed traverse speed), but that area decreased with traverse speed increase (for fixed rotational speed). They also studied the dependence of the stirred zone against groove size and found that stir zone area decreases with increase of the groove width. Rana et al. [11] fabricated surface composite with Al 7075 matrix and B_4C powder reinforcements. They concluded that lower traverse speed means better powder distribution, higher hardness, finer microstructure, and higher wear resistance. In other study [21], where traverse speed was fixed and rotational was varied, hardness increased with rotational speed decrease, and under higher rotational speeds, better uniformity of the microhardness was obtained. In his study, Moustafa [17], achieved high tensile strength at lower rotational speeds (900 and 1200 rpm) and medium traverse speed of 15 mm/min. He also found that increased rotational speed caused defects in the composite, especially under higher traverse speed. Ebrahimzad et al., [19] applied response surface methodology (RSM) in process optimization and proposed optimal rotational speed at 1200 rpm and 40 mm/min traverse speed that corresponds to the best mechanical properties of the composite. In case of other reinforcements (e.g. MWNT), higher rotational speed (1500 rpm to 2000 rpm) improved MWNT distribution in Al 7075 matrix [23]. In general, the optimal range of speeds greatly depends on the type of the substrate material and reinforcements.

3.3 Tilt angle

Tool tilt angle, between tool axis and processing/welding direction, (α) is introduced as a process parameter, ensuring that the tool holds the base material well beneath tool shoulder and allow it to move effectively around pin, during the welding in FSW or modifications in FSP. Typically, the angle between 0^o and 3^o is selected [3,5]. Dialami et al. [33] tested the effects of two tilt angles (0^o and 2.5^o) and concluded that tool tilt angle has impact on stress increase within the leading edge of the tool on the workpiece, as well as on the temperature increase in the neighboring zone of the FSW tool in the rear advancing side. They also found that changes of the tilt angle can decrease the material flow stress in the rear advancing side, facilitate the material flow behind the tool and strengthen the material stirring action at trailing edge on the advancing side. Tilt angle also directly affects tool plunge depth.

3.4 Insertion depth

An appropriate ''insertion depth'' primarily depends on the probe length, but it can influence the quality of the resulting surfaces. Rathee et al. [9] examined the influence of FSP tool insertion depth on the quality of the newly formed composite. SiC powder was reinforcement material. The powder was distributed in Al AA6061-T6 matrix plate (5 mm x 60 mm x 200 mm). Powder was inserted into the groove of 2 mm depth and width. The groove was closed with a pin-less tool. The FSP tool material was H-13 tool steel. The FSP process parameters were: 2.5° tool tilt angle, traverse speed of 40 mm/min, and tool rotational speed of 1400 rpm. Low plunge depth resulted in low material flow and formation of cavities at the center of stirred zone, due to the low heat generation at small contact area between the tool shoulder and the workpiece. They proposed the plunge depth of 0.25 mm (with 20 mm shoulder diameter) as the optimal value. If penetration depth was above the optimum value it resulted in workpiece-tool shoulder sticking; ejection of the reinforcement powder; thinning of the workpiece and even significant damage. Lim et al. [23], found that increase of the shoulder penetration depth improved distribution of MWNT in Al 7075 matrix.

3.5 Tool geometry

Important factor in FSW/FSP is the pin geometry of the FSW/FSP tool. There are many tool pin variations, but the most common, presented in Figure 4, are conical round bottom pin, columnar (cylindrical) pin, threaded columnar pin, threaded columnar pin with flutes, triangular pin and square pin [2,4,32,34]. According to the literature, the most commonly applied are the threaded cylindrical, triangular and square pin profiles. Probes without threads are good for processing harder alloys or metal matrix composites as the threaded features have tendency to wear away more easily. Outer surfaces of the probe can also have flutes or combinations of flutes and threads [2]. Also, some pin profiles can provide pulse type of processing. The higher number of flat surfaces the tool has, the more pulsating work principle will be realised and therefore finer grain size. Threads and flutes can also increase heat input into the material compared to flat surfaced tools, since these can provide better material mixing due to the better stirring.

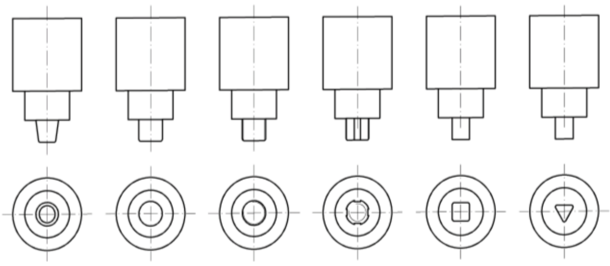

Fig. 4. The most common tool pin geometry FSW/FSP, (from left to right): conical round bottom pin, columnar pin, threaded columnar pin, threaded columnar pin with flutes, square pin and triangular pin.

Elangovan and Balasubramanian [32] compared straight, taper (conical), threaded cylindrical, square, and triangular pin tool geometries and found out that square pin profile shows defect free zones without any correlation to the welding speeds. They also concluded that the best welding speed irrespective to the pin profile, combined with the best pin profile irrespective to the welding speeds acquires maximum tensile strength, hardness and finer grain structure. In terms of surface composite fabrication by FSP it is noted that the most uniform dispersion of the reinforcement particles throughout the matrix is achieved by using the square pin tool when compared to cylindrical (threaded and non-threaded) and triangular [34]. Also, the finest grain structure is obtained using square pin profile, but squared tool showed the highest wear rates, thus leaving iron debris within the aluminium matrix. Azizieh et al., 2011 [35] compared tool pin profile effect on particle distribution in $AZ31/Al_2O_3$ surface composite and concluded that threaded columnar probe produced no defects when compared to non-threaded and fluted cylindrical probe, due to better material flow and stirring.

3.6 Number of passes

Bourkhani et al. [10] found that non-uniformity of their Al/Al_2O_3 composite is more expressed with single pass FSP, in terms of grain structure, tensile properties and particle distribution and with second pass, the higher homogeneity was achieved. Narimani et al. [13] achieved relatively uniform TiB_2 distribution with four passes. García-Vázquez et al. [14] examined one- and two-pass FSP processes where two passes showed better results in hardness and wear resistance, compared to only one pass. In their study, Mirjavadi et al. [16], investigated the influence of multi-pass FSP on $AA5803/ZrO_2$ composite microstructure, mechanical and wear properties and found out that multi-pass FSP improves tensile properties consistently, with pass number increase, while wear rate decreased with pass number increase. Also, friction coefficient was higher at eight-pass FSP than substrate material. Moustafa [17], assessed the multi-pass FSP effects on surface composite $AA2024/Al_2O_3$ and showed the similar results, increasing surface hardness by 40% due to grain refinement. He also concluded that one pass is not enough to form surface composite. Same results are reported in other literature [20]. During the FSW process, increase of number of passes (rewelding) enhances mechanical characteristics of weld joint [36], but higher deformation can occur due to the higher heat inputs.

4. MATERIALS IN FRICTION STIR PROCESSING (FSP)

Material selection of the composite constituents is commonly known to have the highest impact on the composite quality. For FSP, not only the matrix and reinforcements material is important, but also the tool material has significant influence on the resulting composite structure. Short review of the materials pertaining to the fabrication of composites, by using FSP technology, is shown in Table 1.

Table 1. Surface composites produced by FSP found in literature.

Tool material	Substrate material	Reinforcement material	Ref.
H-13 steel H-13 steel	Al 5083-O AA 6061-T6	B_4C SiC	[8] [9]
H-13 steel	AA 1050	Al_2O_3	[10]
WC-12Co	Al 7075	B_4C	[11]
H-13 steel	AA5083	SiC	[21]
HCHCr	AA6082	Al_2O_3 SiC TiC B_4C WC	[12]
H-13 steel	AA6063	TiB_2-10 wt%Al	[13]
H-13 steel shoulder MP159 pin	7075-T651	7075 powder 7075-2%TiC	[14]
HCHCr	AA6082	100% TiB_2 100% TiB_2 + 50 % BN 100 % BN	[15]
HCHCr	AA7075-T6	TiB_2	[24]
H-13 steel	AA5083	ZrO_2	[16]
K-110	AA2024	Al_2O_3	[17]
H-13 steel	AA2024	Al_2O_3	[25]
H-13 steel 50 HRC steel	Al2024 AA2024	Al_2O_3 SiC	[37] [18]
AISI H13	AA7075	MWCNT	[19]
H-13 steel	Al 5083	B_4C	[20]
WC–13 wt% Co	Ti–6Al–4V	TiC	[22]
H-13 steel	AA6061-T	Al_2O_3 TiO_2	[38]
-	Al7075–T6	CNT	[23]

5. FRICTION STIR PROCESSING (FSP) EFFECTS ON THE MECHANICAL PROPERTIES

5.1 Microstructure effects

FSW/FSP surfaces have four different microstructure zones: stirred zone (SZ), also known as the "nugget zone" (NZ), thermo-mechanically affected zone (TMAZ), heat-affected zone (HAZ), and the base material (BM), as shown in Figure 5 [39].

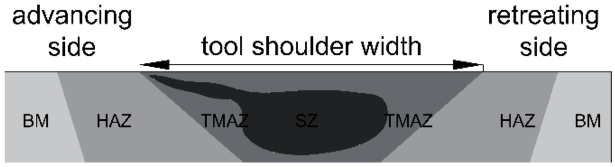

Fig. 5. Microstructural zones in transverse cross-section of the FSW/FSP material. BM – substrate material; HAZ – heat affected zone; TMAZ - thermo-mechanically affected zone; SZ – stirred zone.

Grain size is directly affected by the peak temperature in the stirred zone [40]. With sufficient stirring action and high temperature, large number of fine recrystallized grains can be formed. Rathee et al. [9], observed on microscopic levels that where the tool plunge depth (TPD) was smaller, defects were observed in the center of the stir zone (SZ). With the increase of TPD, uniform powder distribution occurred, and the stir zone was defect-free. The authors have also concluded that with the larger increase of TPD (0.35 mm) defects appear in the stir zone. On the other hand, with some other material combinations (TiC Reinforced Surface Al7075-T651 Aluminium Alloy), almost no cracks and voids appeared except of very small amount within the stir zone [14]. Palanivel et al. [15] identified TiB2 and BN particles homogeneously dispersed throughout the aluminium matrix. Zahmatkesh et al. [37] identified four zones during microstructural observation of FSP workpiece: base material (BM), heat affected zone (HAZ), thermo-mechanical affected zone (TMAZ), and stirred zone (SZ). In their study, there were no defects and reinforcements were evenly distributed. Some research data indicates that FSP decreases grain size and addition of reinforcements such as CNTs, B_4C even more decreased the grain size [19,20,25].

5.2 Hardness

Average hardness of Al7075/B_4C composite led to increase of 1.3 to 1.6 times compared to the metal substrate, as reported in [11]. Sharma et al. [21] found 4.5 times increase in hardness of AA583/SiC composite compared to the base material with 1400 rpm to 40 mm/min speed ratio, while with increase of rotational speed with transverse speed fixed, the hardness was lower. Adding TiB_2 particles to AA6063 matrix increased hardness from 55 HV to 140 HV (2.5 times) [13]. García-Vázquez et al. [14] showed that Al7075 substrate material has higher hardness than Al/TiC FSP fabricated composite. Similar reports can be found also in other literature [18–20,37].

5.3 Wear properties

Bourkhani et al. [10] showed that friction coefficient of aluminium can be reduced by forming a thin composite layer on the surface (AA1050 matrix reinforced by Al_2O_3 particles. This can be explained with strength and wear resistance increase and reduction in contact area between the steel counterpart and fabricated composite rather than changing in the material structure [10]. García-Vázquez et al., [14] exhibited increases in wear rate coefficient comparing to the Al 7075 substrate. Palanivel et al. [15] used FSP process to add TiB_2 powder as reinforcement into AA7075 which led to the sliding wear resistance increase. Rajan et al., [24] enhanced mechanical and wear properties of AA7075 matrix with adding TiB_2 and these properties improved even more after FSP. Addition of reinforcement particles changed wear mode from adhesive to abrasive and FSP made wear more uniform, and also the wear debris became finer after FSP. Similar results are also reported in [19,20,38].

5.4 Tensile strength

Narimani et al. [13] increased tensile strength of AA6063, up to 70% by addition of TiB_2-Al particles and FSP. Similar results are reported in [24]. Moustafa [17], achieved tensile strength improvement with multi-pass processing with superior improvement at lower rotational speeds and medium traverse speed. The application of FSP increased tensile and yield strength on both unreinforced [19,25] and composites produced by the compocasting [19,20,25]. However, behavior of the composites processed by the FSP method still needs data from aspects of their mechanical performance as well as different other influential factors.

5.5 Fracture and defects formation

Rajan et al. [24] discovered that addition of TiB_2 particles in AA7075 alloy reduced the void size in the fracture surface, which became even finer after FSP. Mirjavadi et al. [16] compared fracture surfaces of eight-pass FSP processed material in comparison to the base material and found similar structure, characteristic for a ductile fracture, with networked dimples and voids. FSP is proven to be a very efficient method for treating the porosity defects formed through casting in terms of the shrinking cavities [25]. Tool pin profile has a very significant role for the porosity and defect formation, as well. However, the appropriate selection of the pin profile to simultaneously provide the highest material flow and low wear rates, is still a challenge.

6. CONCLUSION

The friction stir processing (FSP) has emerged as one of the efficient methods to produce thin composite surface layers by addition of the reinforcement particles within a substrate matrix. FSP can be also used just to modify the surface structure, without reinforcements, through the influence of the processing on the base material structure. Aluminium is one of the mostly used materials as the base material for the FSP process (approximately 70 percent), due to the relevance for the transport industry in general of both the Al-based alloys and FSP as a new technology for the improvement of surface layers, especially in structural components.

However, FSP technology still needs comprehensive research from many aspects, including the influence of the process and material properties on the final quality, as well as the final functional behavior of the produced elements over time. In order to produce a defect-free, surface composite, with uniform reinforcement of particles within a matrix, it is necessary to achieve optimal compromise in terms of the FSP parameters (speeds, axial force, tool tilt angle, tool pin profile). Selection of the reinforcements is also of the utmost significance and optimal composite constituents are commonly determined depending on the final application, but it still needs research since existing data are scarce.

FSP showed many benefits, with major one being the processing at the room temperature, also without the need for additional heat treatments in post-processing. In the case of Al-based alloys, FSP resulted in refinement of the grain structure and microhardness increase. Appropriate selection of the reinforcement particles and processing regimes can greatly increase the wear resistance.

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