

REVIEW ARTICLE

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# Different strategies of secondary phase incorporation into metallic sheets by friction stir processing in developing surface composites

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## Abstract

Friction stir processing (FSP) is a solid-state processing method, which recently gained wide popularity to modify the microstructure of metallic surfaces and to produce surface composites. For the past decade, composites of different materials such as aluminum, copper, magnesium, titanium, and their alloys were successfully produced by FSP. The amount of secondary phase that is dispersed at the surface of the workpiece during FSP and the level of dispersion depend on many factors such as tool design, processing parameters, and type of material. Recently, the method of secondary phase incorporation into the surface metals was also considered as an important factor in developing surface composites by FSP. A few strategies such as groove filling, holes filling, sandwich method, direct method, and surface coating followed by FSP methods have been developed as promising ways of secondary phase incorporation into the surface of the materials during FSP. The aim of this review paper is to give a comprehensive summary of different methods developed to disperse the secondary phase into the surface of the workpiece during FSP to produce surface composites. The strategies have been explained, compared, and discussed to suggest an appropriate method based on the requirement to adopt in developing surface composites.

**Keywords:** Friction stir processing, Surface composites, Secondary phase, Dispersing methods

## Review

### Introduction

Friction stir processing (FSP) is a solid phase processing technique, developed to alter the microstructure of metallic sheets without melting the material and by inducing intense plastic deformation with the help of a rotating non-consumable tool that contains a pin at the end (Mishra and Ma 2005). FSP has also been widely used to produce different metallic surface composites. Surface composites are a class of materials in which the surface contains dispersed secondary phase, and the core of the material remains the same. Centrifugal casting, chemical or physical vapor deposition, plasma spraying, and laser treatment are a few methods have been developed to produce surface composites (Kapranos et al. 2014; Nikhilesh

and Krishan 2013; Ayers and Tucker 1980). All these techniques involve melting of the substrate except FSP in which material does not melt (Mishra and Ma 2005). Developing composites in solid state using FSP can address the issues associated with melting and solidification usually found in conventional processes. Aluminum, copper, titanium, magnesium, and their alloys are the mostly used metals as matrix materials and SiC (Mishra et al. 2003; Alidokht et al. 2013; Barmouz et al. 2011; Devaraju et al. 2013), WC (Khosravi et al. 2014), MoS<sub>2</sub> (Alidokht et al. 2013), Al<sub>2</sub>O<sub>3</sub> (Devaraju et al. 2013; Raft et al. 2011; Yang et al. 2010; Sharifitabar et al. 2011; Devaraju et al. 2013; Azizieh et al. 2011; Faraji et al. 2011), CNTs (Liu et al. 2013; Morisada et al. 2007; Morisada et al. 2006), B<sub>4</sub>C (Madhusudhan Reddy et al. 2013; Sathiskumar et al. 2013a), Ni particles (Devinder and Bauri 2011), carbon fibers (Mertens et al. 2012), TiC (Sabbaghian et al. 2014), hydroxyapatite (Ratna Sunil et al. 2014a; Ratna Sunil,

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et al. 2014b; Farnoush, Sadeghi, et al. 2013; Farnoush, Bas-tami, et al. 2013), and graphite (Soleymani et al. 2012) are the widely used dispersing phases in producing surface composites using FSP.

Several studies have been carried out to estimate the potential of FSP to produce surfaces with enhanced surface hardness, wear resistance, and corrosion resistance and were clearly demonstrated in the literature (Faraji et al. 2011; Liu et al. 2013; Devinder and Bauri 2011; Ratna Sunil et al. 2014a; Ratna Sunil et al. 2014b; Soleymani et al. 2012; Mishra et al. 2014). The success of producing a composite using FSP depends on many factors such as tool design, processing parameters, and type of the material (Mishra et al. 2014). Recent studies have clearly shown the method of secondary phase introduction during FSP also influence the amount and level of secondary phase distribution at the surface (Gandra et al. 2011; Miranda et al. 2013). Therefore, the objective of the present review is to give a comprehensive summary of different methods developed to incorporate secondary phase into the surface of the material in developing composites using FSP with an emphasis given to compare and discuss the methods.

### **Composite fabrication by friction stir processing (FSP)**

The stirring action of FSP tool can be used to incorporate and distribute secondary phase into the surface of a metallic sheet or plate, and a surface composite can be produced by FSP. As the FSPed region contains fine grains, after composites produced by FSP also exhibit fine grain structure (Mishra et al. 2014; Ratna Sunil et al. 2012; Ratna Sunil et al. 2014). Therefore, grain size reduction is another advantage along with incorporating the secondary phase particles in developing surface composites by FSP. Initially, Mishra et al. (2003) successfully demonstrated producing Al-SiC composite using FSP. Later, there are numerous studies carried out to develop different metal matrix composites using FSP. Usually, the secondary phase is in the form of particles filled in grooves or holes produced on the surface of the material, and then FSP is carried out to disperse the secondary phase into the matrix metal. These secondary phase particles are dispersed in solid state itself during FSP due to the material flow resulted from the plastic deformation of the matrix material. The level of distribution of these particles within the matrix depends on many processing parameters. The mechanism of material flow during FSP is clearly explained by Arbegast (Arbegast 2003; Arbegast 2008), which involves several independent deformation processes such as extrusion and forging along with simultaneous localized heating and cooling.

### **Different methods of secondary phase incorporation into the matrix by FSP**

The way how the secondary phase is introduced into the matrix material is also one of most influencing factors that affects the successful fabrication of the composite using FSP besides many influencing parameters such as (i) tool geometry which includes shoulder diameter, pin profile, and dimensions; (ii) processing parameters such as tool travel speed, rotational speed, and load; and (iii) material type. There are different methods reported in the literature to incorporate the secondary phase into the matrix material during FSP, and every method has its own advantages and limitations.

#### **Groove filling method**

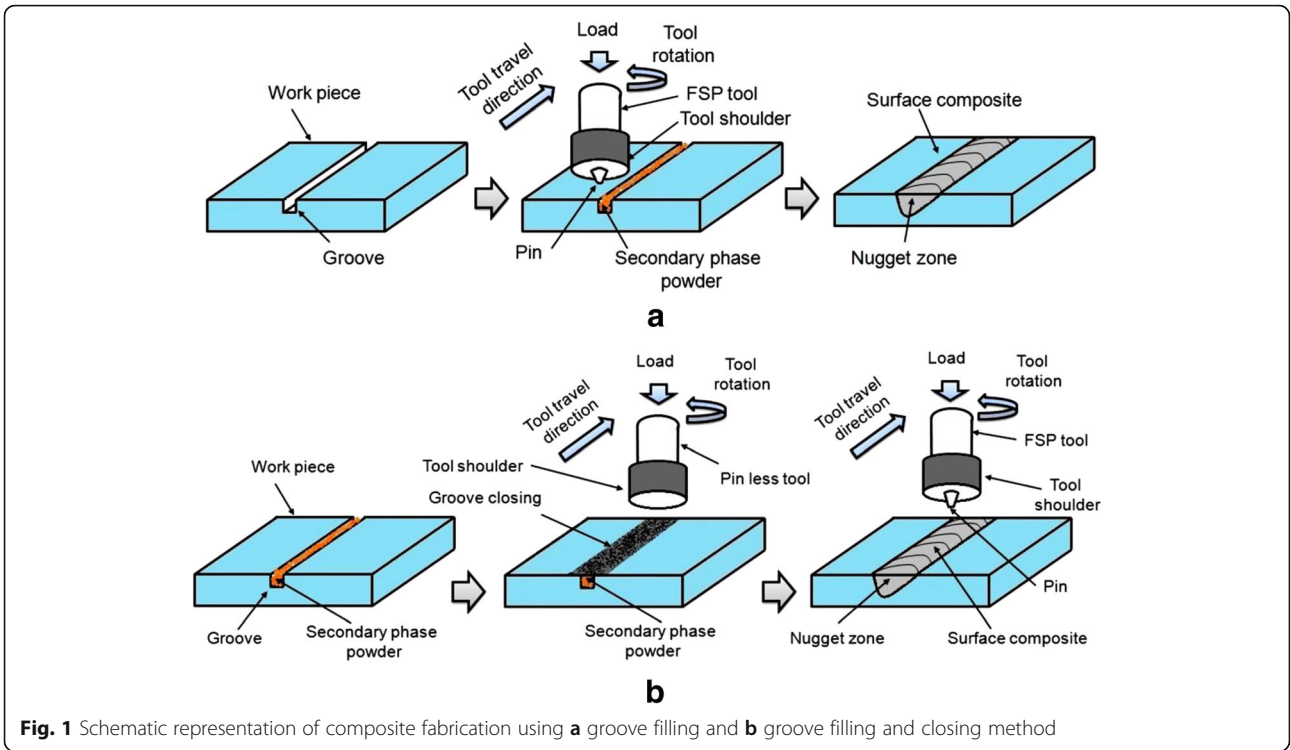
This was the first method introduced by Mishra et al. (2003) while producing Al-based composites. In this method, a narrow groove is produced on the surface of the sheet or plate before FSP and the groove is filled with the secondary phase particles. Then FSP is carried out to develop surface composite (Mishra et al. 2003; Ratna Sunil et al. 2014a; Ratna Sunil et al. 2014b). Figure 1a shows the schematic representation of groove filling method. Later on, groove filling and closing method was also reported (Lee et al. 2006) in which a groove is produced on the surface and filled with secondary phase, and the groove is closed by surfacing the groove using a non-consumable tool which does not contain a pin at the shoulder as shown in Fig 1b. Due to the applied load, heat is generated because of the friction between the flat shoulder of the tool and the surface of the workpiece. Therefore, the surface of the groove undergoes plastic deformation and is closed to facilitate the filled particles not to fly away or escape from the groove during FSP.

#### **Holes filling method**

Holes filling method is another way of incorporating the secondary phase particles into the matrix during FSP (Yang et al. 2010; Akramifard et al. 2014). A few tiny holes are produced on the surface of the workpiece and the holes are filled with the secondary phase, and FSP is carried out to produce the surface composites as shown in Fig. 2a. Similar to that of groove filling and closing method, another development happened in this method which needs two processing tools; one without pin and second with a designed pin at the shoulder (Madhusudhan Reddy et al. 2013). After filling the holes with the secondary phase, the holes are closed with the help of pin-less FSP tool as shown in Fig. 2b and then FSP is carried out to develop surface composites.

#### **Sandwich method**

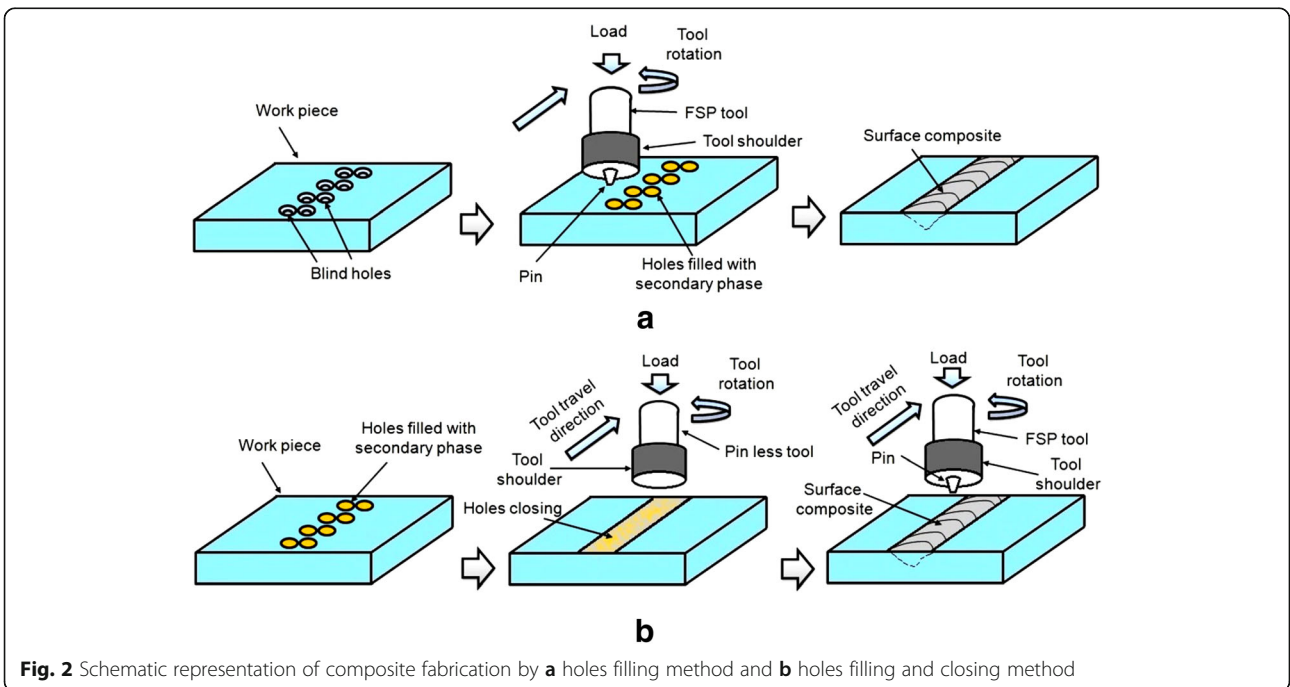
This is another way of developing surface composites using FSP. Initially, the method was explained by Mertens et al.



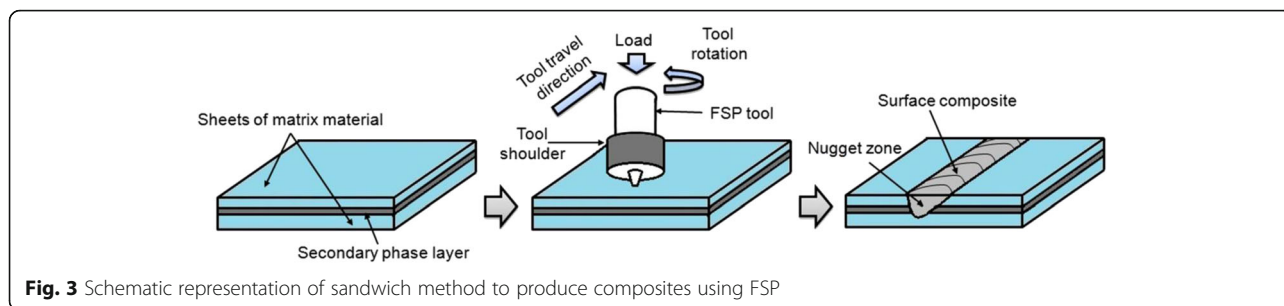
**Fig. 1** Schematic representation of composite fabrication using **a** groove filling and **b** groove filling and closing method

(2012). In sandwich method, secondary phase is placed in the form of a layer or lamina between sheets or plates of matrix material and FSP is carried out. Due to the stirring action and traverse motion of the FSP tool, the secondary phase layer or lamina is broken into small particles or

fibers, and the matrix phase and the secondary phase are mixed to form a composite. By arranging more number of layers, the quantity of dispersing phase into the matrix can be increased. As the number of FSP passes is increased, uniform dispersion of the particles was clearly observed



**Fig. 2** Schematic representation of composite fabrication by **a** holes filling method and **b** holes filling and closing method



**Fig. 3** Schematic representation of sandwich method to produce composites using FSP

in the work of Merents et al. (2012). Figure 3 shows schematic representation of sandwich method.

**Direct friction stir processing (DFSP) tool method**

Huang et al. (2014) proposed a new kind of FSP tool that contains a hole along the longitudinal axes of the tool through which secondary phase powder is supplied during FSP and named the tool as direct friction stir processing (DFSP) tool. Figure 4 shows the schematic representation of DFSP process, and Fig. 5 shows the typical photograph of DFSP tool. In this method, during the process, secondary phase particles are supplied through a continuous hole provided in the DFSP tool itself. The mechanism behind the composite formation using this modified tool has been explained by the authors. Unlike in FSP, the reinforcement particles are not introduced into the surface of the base metal before processing but supplied through the hole which is designed within the DFSP tool. As the tool is moved in the traverse direction at the surface of the work piece, the reinforcement particles are directly placed within the space formed between the shoulder of the DFSP tool and the workpiece. Therefore, the particles are not escaped during the process but entrapped between the concave space of the shoulder and the surface of the workpiece. Then, these entrapped particles are stirred and pressed into the workpiece uniformly to produce the surface composite. As described by the authors, in a single pass, more amount of secondary phase

can be introduced into the matrix using DFSP tool compared with that of FSP tool.

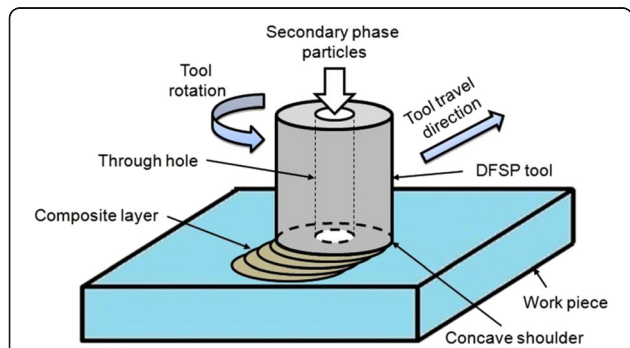
**Surface coating followed by FSP method**

Providing the surface coatings on the material before FSP is another strategy to incorporate the secondary phases into the matrix material (Mazaheri et al. 2014; Kurt et al. 2011). Secondary phase is coated on the surface by any suitable coating technique before FSP. Then the coated sheet is processed using an FSP tool as shown in Fig. 6 to produce the surface composite. Due to the plastic deformation and material flow as the rotating FSP tool travels across the coated surface, matrix material and secondary phase are properly mixed and results a composite layer.

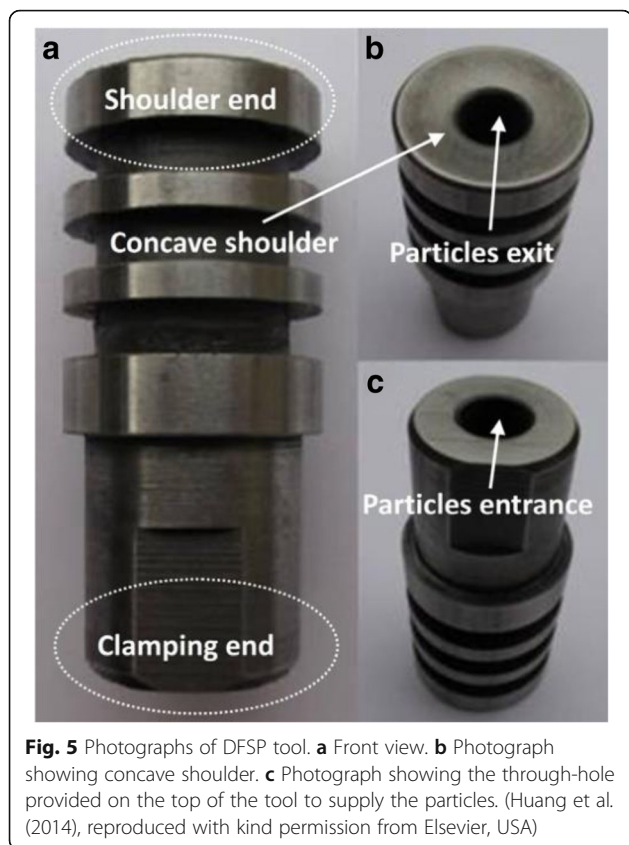
**Discussion**

Producing composites by FSP is a promising technique that has more potential in developing metal matrix composites. However, incorporating the secondary phase and control over the distribution of secondary phase is crucial while using FSP as the processing method. The martial flow during FSP is complex in nature (Arbegast 2003). However, optimizing the process parameters can address the distribution of the secondary phase during FSP. Along with the other influencing factors such as tool design and processing parameters, method of secondary phase incorporation is also found to have a major role in distributing the powder particles and producing a successful composite (Gandra et al. 2011; Miranda et al. 2013). The thickness of the composite layer produced using FSP depends on the method of secondary phase incorporation. Table 1 lists the maximum thickness of the composite layers produced on the surface of different material systems using different strategies of secondary phase incorporation by FSP.

Groove filling was the first method proposed in the literature to produce a composite by FSP (Mishra et al. 2003). It is simple and requires less machining. A straight groove can be produced on the workpiece using ordinary milling cutter. Recently, Gandra et al. (2011) has studied the position of the groove with respect to the tool pin and demonstrated that if the groove is placed under



**Fig. 4** Schematic representation of DFSP tool method (source: Huang et al. (2014))

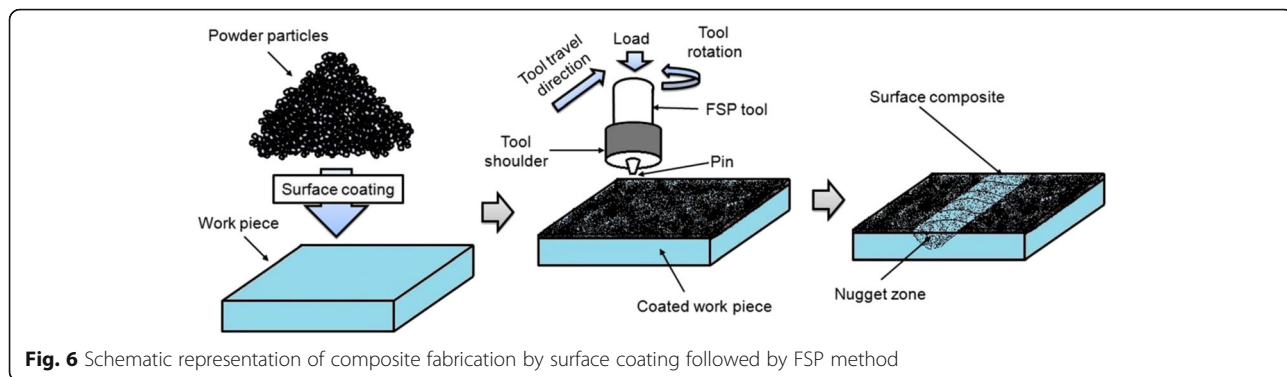


the pin, the powder distribution is found to be more compared with placing the groove outside the pin interaction area (advancing or retrieving). Another strategy was proposed by Heydarian et al. (2014) in groove filling method in which parallel grooves with gradient groove depths were produced and FSP was carried out. Compared with single groove, composite produced from the gradient grooves was found to have uniform distribution of the powder. Whereas the groove filling and closing method needs additional tools such as pin-less FSP tool, and also the process involves two cycles; one to close the groove, and the second to produce the composite. The amount of secondary phase that can be introduced into

the workpiece is more in groove filling and closing method compared with simple groove filling method because it prevents the escape of filled particles during FSP.

Holes filling method gives possibility to introduce more quantity of powder compared with that of groove filling method. Escape of the powder during FSP is less in holes filling method compared with that of groove filling method. Similarly, holes filling and closing method gives more control over the particle incorporation compared with that of groove filling and holes filling methods but requires more operations. For applications, where more quantity is not necessary but slight modification is enough to alter the surface properties, simple groove filling method or groove filling and closing method can be adapted. Groove filling method is also appropriate to obtain thick composite layers compared with other processes as shown in Table 1. Of course, the thickness of a composite layer depends on the FSP tool pin dimensions and processing parameters. Where applications demand more amount of secondary phase at the surface, holes filling or holes filling and closing method can be chosen.

Compared with these groove filling and hole filling methods, sandwich method does not require any machining process before FSP. Also, it reduces the necessity of using additional tool (without pin) to close the groove or holes before FSP. As reported by Faraji et al. (2011) the distribution of secondary phase is uniform in sandwich method. But making the secondary phase into the form of layers or laminas is difficult particularly with hard and brittle ceramic materials. Also, the secondary phase may present in the matrix in the form of large particles after FSP as there is no control over the breakdown of the layers during the process. There are a few studies clearly demonstrated that if the dispersing particle size is reduced, the surface properties were found to be improved (Liu et al. 2013; Morisada et al. 2007; Sabbaghian et al. 2014; Ratna Sunil et al. 2014a; Ratna Sunil et al. 2014b; Miranda et al. 2013). Therefore, in sandwich method, control over the size of secondary phase particle resulted



**Table 1** Maximum thickness of surface composite layer achieved in different material systems using FSP and the corresponding method used to incorporate the secondary phase into the matrix

Material system	Secondary phase	Method of secondary phase incorporation	Composite layer thickness (mm)	Reference
Aluminum/its alloys	SiC	Groove filling	2	Wang et al. (2009)
	Al <sub>2</sub> O <sub>3</sub>	Groove filling and closing	4	Shafiei-Zarghani et al. (2009)
	MWCNTs	Groove filling	2.2	Lim et al. (2009)
	Al <sub>2</sub> O <sub>3</sub>	Holes filling	3	Yang et al. (2010)
	SiC and MoS <sub>2</sub>	Groove filling	3.5	Alidokht et al. (2011)
	Ni particles	Groove filling	0.15	Devinder and Bauri (2011)
	Al <sub>2</sub> O <sub>3</sub>	Groove filling and closing	3.8	Sharifitabar et al. (2011)
	TiC B <sub>4</sub> C	Groove filling	6	Maxwell Rejil et al. (2012)
	Graphite, Al <sub>2</sub> O <sub>3</sub> , and SiC	Groove filling	3.5	Anvari et al. (2013)
	SiC and Al <sub>2</sub> O <sub>3</sub>	Surface coating and FSP	0.204	Miranda et al. (2013)
	Al <sub>2</sub> O <sub>3</sub>	Surface coating and FSP	0.1	Mazaheri et al. (2014)
	Magnesium/its alloys	SiO <sub>2</sub>	Groove filling and closing	3–3.5
CNTs		Groove filling	2	Morisada et al. (2006)
SiC		Groove filling and closing	2.5	Asadi et al. (2011)
Al <sub>2</sub> O <sub>3</sub>		Groove filling	5–6	Azizieh et al. (2011)
Al <sub>2</sub> O <sub>3</sub>		Groove filling	2–2.5	Faraji et al. (2011)
Carbon fibers		Sandwich method	2.7	Mertens et al. (2012)
SiC and B <sub>4</sub> C		Holes filling and closing	3	Madhusudan Reddy et al. (2013)
SiC		Direct friction stir processing tool	0.15	Huang et al. (2014)
Hydroxyapatite		Groove filling	2	Ratna Sunil et al. (2014b)
Copper/its alloys	SiC	Groove filling	2	Barmouz et al. (2011)
	Graphite	Groove filling and closing	Not reported	Sarmadi et al. (2013)
	B <sub>4</sub> C	Groove filling and closing	5	Sathiskumar et al. (2013b)
	TiC	Holes filling and closing	Not reported	Sabbaghian et al. (2014)
	SiC	Holes filling	Not reported	Akramifard et al. (2014)
Titanium/its alloys	Hydroxyapatite	(i)Groove filling (ii)Surface coating	0.16	Farnoush et al. (2013)
	Hydroxyapatite	Holes filling	0.16	Farnoush et al. (2013)
Steels	TiC	(iii)Groove filling (iv)Surface coating	1.5–2	Ghasemi-Kahrizsang and Kashani-Bozorg (2012)

from the FSP within the matrix is very poor and completely depends on the processing parameters and the design of the tool.

Another interesting development in the method of particle incorporation during FSP is application of direct friction stir processing (DFSP) tool as proposed by Huang et al. (2014). Initial machining processes such as producing grooves or holes to fill the secondary phase particles on the surface of the workpiece or need of another pin-less tool to close the groove or holes can be completely eliminated by using DFSP tool which is an advantage. This approach in tool design introduces the secondary phase particles into the surface effectively. However, the penetration depth (thickness) is the main limitation

in DFSP method. The thickness of surface composite layer produced by DFSP is relatively less compared with the surface composite produced by FSP, and tool fabrication is also complex. But the level of uniformity in the distribution of the secondary phase is superior compared with other methods. Overall, this tool design showed interesting results in developing surface composites by FSP, and in future, this design may be used to develop wide variety of metallic surface composites. Providing surface coating on the workpiece by different means before FSP has also shown promising results in successfully developing the surface composites. More amount of secondary phase can be introduced into the surface, but the thickness of the produced composite layer is less

compared with the composites produced by the other methods. Similar to DFSP tool method, surface coating followed by FSP method gives the modified surface depth limited to a few hundreds of micrometers from the surface. Also, pre-coating requires additional processing which increases the overall work to produce a composite.

Based on the required thickness and the amount of secondary phase that is required to be dispersed at the surface of the workpiece, appropriate method can be chosen in developing surface composites using FSP. Among all of the methods proposed in the literature, one common limitation is producing composites with tailored composition. The composition of the composites produced by FSP can be approximately assessed by assuming that the dispersion is uniform. However, exact amount of secondary phase that is distributed in the matrix material is not the same throughout the processed region. Variation in the distribution of secondary phase also influences the material properties if not macroscopic but microscopic level. Majority of the work is being carried out on developing different composite systems, but focus on developing strategies to address these issues is inferior. Developing new strategies to increase the level of incorporation, distribution of secondary phase, and increasing the thickness of the affected surface layer is in a great need to utilize the high potential of FSP technique in producing surface composites. For example, Asadi et al. (2010) studied the effect of penetration depth (PD) of FSP tool and demonstrated that the PD also has a great influence on composite formation. Further, the authors have shown the effect of (PD) on composite formation again depends on tool travel and rotational speeds. But, the composite layer thickness was not clearly reported. Investigating the combined effect of method of particles incorporation, process parameters, and type of tool on successful fabrication of surface composites by FSP also enhance the knowledge to address challenges involved in this area. Composite fabrication using FSP has wide industrial applications, and also the process does not require huge capital investments. Existing computer numerical control (CNC) machines can be modified with appropriate attachments and FSP can be carried out. Therefore, industries can easily and rapidly adopt the process.

## Conclusions

It has been well demonstrated that FSP has a great potential in developing metallic surface composites in solid state itself. Different methods were proposed to incorporate secondary phase particles into the surface of the workpiece during FSP. Groove filling, holes filling, sandwich, DFSP, and surface coating followed by FSP are the widely used methods to incorporate the secondary phase into the

metallic surfaces using FSP. Groove filling or holes filling followed by closing groove or holes using flat shoulder (pin-less) tool prior to FSP has shown optimum method to disperse more amount of secondary phase. Other new methods such as sandwich method, direct FSP tool, and surface coating method also have shown interesting results. However, research on developing these strategies and need of new strategies to produce tailored composites is in a great need to make the FSP technique as a promising method for industrial applications.

## Competing interests

The author declares that there is no conflict of interest directly or indirectly related to the present research work.

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