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铝基复合材料搅拌摩擦加工制备工艺及其耐磨性能研究进展

刘傲翔,王江涛*,李星辰,何明涛,胡可军,谢利,刘超,王明智
(江苏理工学院材料工程学院,江苏 常州 213001)

摘要: 铝基复合材料具有密度低、加工性能良好、耐腐蚀等特点,在高性能制造方面拥有举足轻重的地位,被广泛应用于航空航天、船舶机械等领域。然而,在往复运动的工况条件下,工件之间的磨损对材料的性能影响最为显著,从而降低工件的服役寿命。因此,提高工件耐磨性能和延长服役寿命,对于扩展铝合金的使用范围具有非常重要的意义。在制备铝基复合材料的工艺中,搅拌摩擦加工(Friction stir processing,FSP)技术是制备复合材料的新兴方式之一,所制备的复合材料具有优异的微观组织、不易产生界面反应等特点。所以,搅拌摩擦加工技术在铝基复合材料的生产中有巨大的应用潜力。针对搅拌摩擦加工制备铝基复合材料进行了综述,重点介绍了增强相的种类和含量,以及搅拌摩擦加工中的搅拌道次和焊接等参数,并且讨论了上述因素对铝基复合材料耐磨性能的影响。结果表明:随着增强相含量的增多,铝基复合材料的耐磨性能增强,但过多的含量反而会导致耐磨性能降低;随着搅拌道次的增加,有利于晶粒的细化,但是晶粒的细化程度过高,反而降低了铝基复合材料的耐磨性能。在此基础上,还研究了提高耐磨性能的机理。结果表明,在往复磨损过程中,材料的亚表层易形成动态再结晶,而动态再结晶尺寸对复合材料的耐磨性能有影响,过小的结晶尺寸会使耐磨性能下降。此外,还指出了搅拌摩擦加工制备铝基复合材料过程中存在的问题,如纳米增强相的团聚现象,以及选取适合FSP的工艺窗口等。最后,对FSP未来的研究趋势进行了展望。

关键词: FSP;铝合金;铝基复合材料;增强相种类;增强相含量;搅拌道次;焊接参数;耐磨性能

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0　引言

铝合金具有密度低、加工性能良好、耐腐蚀等特点,被广泛应用于航空航天、船舶机械等领域[1-3]。然而,铝合金结构件在服役环境中受到不同方式的磨损(如往复滑动、侵蚀及磨损腐蚀等[4]),大大降低了其使用寿命。因此,除了硬度、拉伸强度等力学性能外,部分铝合金结构件需要考虑耐磨性。基于此,学者们针对提高铝合金的耐磨性能进行了大量的研究,主要集中于提高铝合金的耐磨性方面。

1　铝基复合材料概述

复合材料可分为金属基复合材料[5-8](Metal matrix composites,MMCs)、陶瓷基复合材料[9-12](Ceramic matrix composite,CMC)、聚合物基复合材料[13-14](Polymer composites,PMC)等。MMCs通常是以金属或者合金为载体,以碳纤维、增强相等为第二相的复合材料,其优势在于既可以保留载体本身的性能,又具有复合材料的综合性能,如耐磨性能[15-16]、疲劳性能[17]等。目前,MMCs材料以铝基、镁基和钛基复合材料为主,在工业中应用较为广泛的是铝基复合材料(Aluminum matrix composites,AMCs)。AMCs是以铝合金或者纯铝为基体,通过引入增强相,按照使用的情况采用不同的工艺所制备。AMCs的研究和应用源于上世纪50年代,DWA公司和麦道公司等将其应用在导流叶片、战机腹鳍和蒙皮等零部件上[18]。在国防军事领域,哈尔滨工业大学研发了SiCp/Al均匀复合材料,应用于导弹、运载火箭等兵器领域[19],因此铝基复合材料的研究一直是研究的热点。

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作者简介: 刘傲翔,硕士研究生,研究方向为搅拌摩擦加工制备铝基复合材料。E-mail:lax20230304@163.com。
通信作者: 王江涛,博士,教授,研究方向为铝合金及其焊接头的改性处理。E-mail:jiasqq1225@126.com。

2 铝基复合材料制备工艺

铝基复合材料的制备工艺包括搅拌铸造[20]、原位自生铸造[21]和粉末冶金[22]等。搅拌铸造、原位自生铸造作为制备铝基复合材料的传统工艺,属于液态铸造。搅拌铸造法是将铝基体金属放置坩埚内加热熔化,随后加入增强相并进行搅拌,其制备原理如图1所示[23]。搅拌铸造法是在高速的搅拌作用下将增强相与基体结合在一起,通过浇铸成型得到铝基复合材料。然而,该法所制备的铝基复合材料存在一定的缺陷,如在搅拌过程中容易引入气体,导致内部存在孔洞缺陷,大大降低了材料的使用寿命。

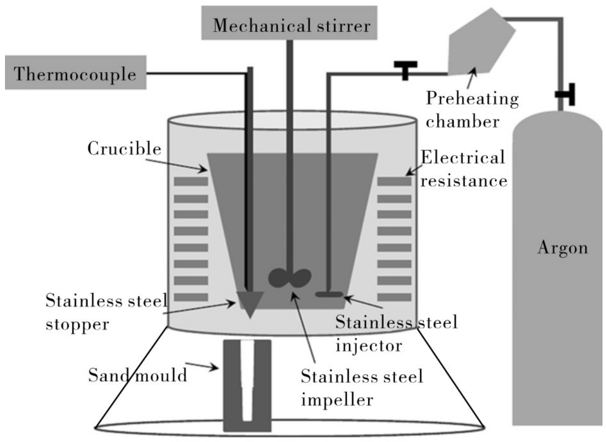


图1 搅拌铸造制备原理示意图[23]

Figure 1 Schematic diagram of stir casting preparation principle

原位自生铝基复合材料的制备,是将一定配比的增强相加入熔融的铝熔液中,使其在高温铝液中反应生成所需的增强相颗粒[24]。该法与搅拌铸造法相同之处,在制备过程中容易发生界面反应,同时会存在偏析或者团聚等缺陷。

粉末冶金的制备工艺相对简单,能够实现增强相的分散,在制备金属基复合材料的制备中同样应用广泛。传统的粉末冶金铝合金工艺是通过一系列工序来制备坯料,这些工序包括原料粉末制备、粉末混合、粉末压实、脱模、真空脱气、烧结等,随后通过热处理或塑性加工等方法进行二次处理,最终制成铝及铝基复合材料。如果烧结后的零件已经达到了设计要求,就不需进行其他加工,从而减少了加工成本。但是,粉末冶金制备过程中易发生氧化现象,造成材料的缺陷较多,不利于使用。图2为传统粉末冶金工艺流程示意图[25]。

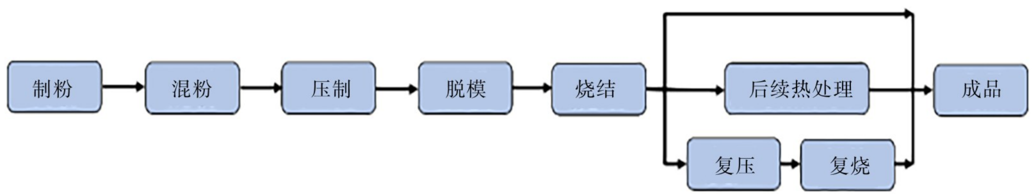


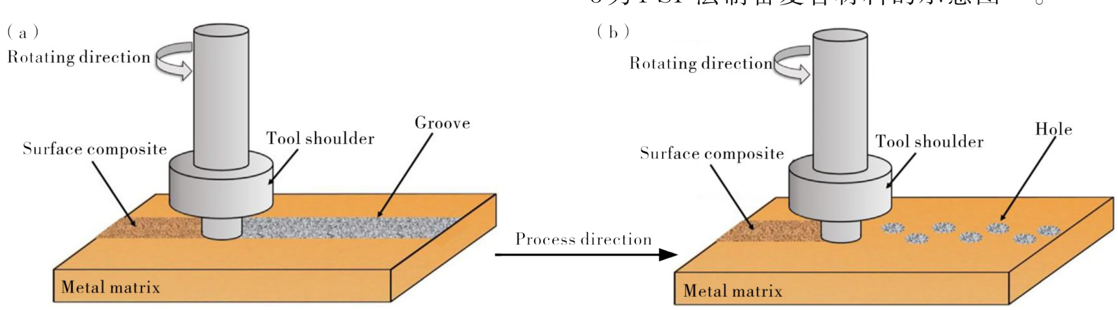
图2 传统粉末冶金工艺流程[25]

Figure 2 Conventional powder metallurgy process

搅拌摩擦焊(Friction stir welding,FSW)作为一项新兴的固相焊接技术,在焊接领域中得到了广泛的认可。搅拌摩擦加工(Friction stir processing,FSP)与FSW的原理相同[26],是制备复合材料的非常重要的关键技术之一。FSP优势在于可细化铝合金[27]和增强相,避免熔化焊中常见的缺陷(如孔洞、裂纹等),减少有害气体和烟尘的产生。

3 FSP法制备铝基复合材料

FSP法制备铝基复合材料,首先在板材上打孔[28-29]或开槽[30-31],然后将增强颗粒填入其中,并以物理的方式进行压实,最后采用FSP进行处理。图3为FSP法制备复合材料的示意图[32]。



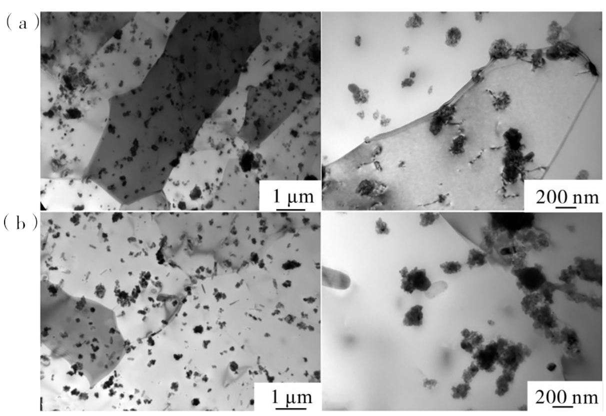
(a)—开槽;(b)—打孔。

(a)—groove filling; (b)—hole filling.

图3 FSP法制备方式[32]

Figure3 Preparation method

王智[33]等利用6061-T6的板材，以打孔的方法添加粒径约为17 μm的高熵合金(HEA)颗粒，在焊接速度为60 mm·min^{-1}、旋转速度为1 000 r·min^{-1}条件下进行水下搅拌摩擦加工制备铝基复合材料。HEA颗粒促进了动态再结晶，使得晶粒得到了细化，经5道次的搅拌摩擦加工后HEA粉末均匀地分布在Al基体中。窦程亮[34]等也运用打孔的方式，将粒径约为80 μm的SiC颗粒填入孔内，在焊接速度及旋转速度分别为600 mm·min^{-1}和1 000 r·min^{-1}下，采用FSP法制备的复合材料最大抗拉强度达到78 MPa、断后的延伸率为18%，从断口形貌发现存在SiC颗粒的位置处出现了大韧窝，表明了复合材料的塑性变形能力得到了提高。Orłowska[35]等在超细晶的铝板上进行开槽，并添加粒度约78 nm的纳米级Al_2O_3增强颗粒，在旋转速度3 200 r·min^{-1}、移动速度50 mm·min^{-1}下，采用FSP法制备铝基复合材料，所制备材料的延伸率达到23%，并且纳米级Al_2O_3颗粒分布均匀且团聚颗粒的尺寸降低(见图4)，性能得到提高，因Al_2O_3增强颗粒阻碍了搅拌区晶粒的生长。Yelamasetti[36]等以打孔方式添加B_4C增强颗粒，在旋转速度1 200 r·min^{-1}、焊接速度30 mm·min^{-1}下，采用FSP法制备复合材料，B_4C的引入使得复合材料的拉伸强度提高了11%(见图5)。Nathan[37]等在凹槽内添加增强石墨烯颗粒，使FSP法制备的复合材料韧性得到提高，导热系数提高了38%。



(a)—TMAZ;(b)—SZ。

图4 FSP超细晶铝的TEM图[35]

Figure 4 FSPed ultrafine crystalline aluminum TEM results

综上所述，通过添加增强相，采用FSP法制备的铝基复合材料，其力学性能得到提高，但针对耐磨性的研究还需要进一步的讨论。

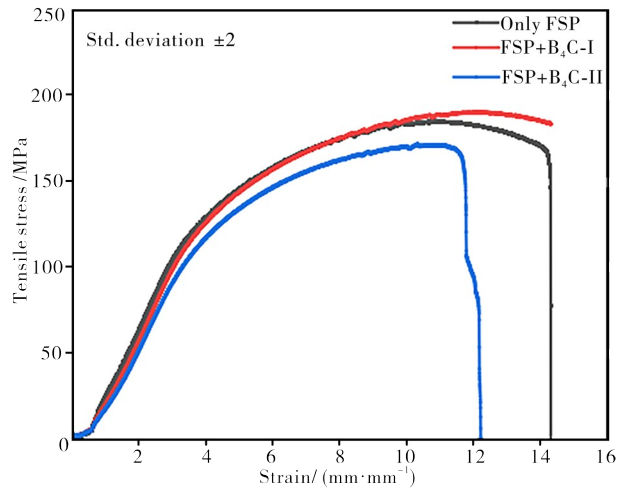


图5 添加B_4C前后复合材料的拉伸曲线[36]

Figure 5 Stretch curve before and after adding B_4C

4 FSP制备铝基复合材料耐磨性能的影响因素

磨损、断裂和腐蚀是机械装备失效的3大形式。磨损主要发生在材料表面，其会引发一系列的零件损伤，最终导致零件的失效[38]。当材料耐磨性能提高时，材料表面的损失速率就会降低，从而降低了磨损损伤。在FSP制备复合材料的过程中，存在多种影响复合材料耐磨性能的因素，如增强相[39]、FSP焊接工艺[40]等。改变增强相的种类和含量，以及选择适宜的焊接工艺窗口，能有效地提高复合材料的耐磨性能。图6为影响复合材料耐磨性的因素。

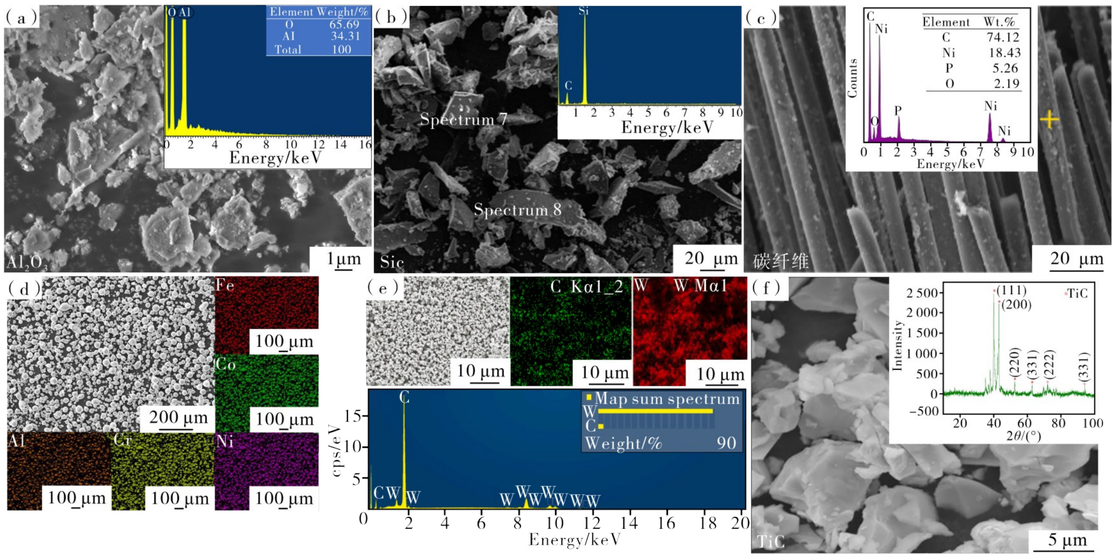
图6 影响复合材料耐磨性的因素[39-40]

Figure 6 Factors affecting the wear resistance of composites

4.1 增强相种类

制备复合材料的增强相种类繁杂，以陶瓷颗粒、碳纤维为主，图7为增强相种类划分[41-46]。

Bharti[47]等以Al_2O_3为增强相，通过对AA6061铝合金进行2道次FSP，结果发现：Al_2O_3的添加提高了材料的耐磨性能，平均摩擦系数达到了0.147



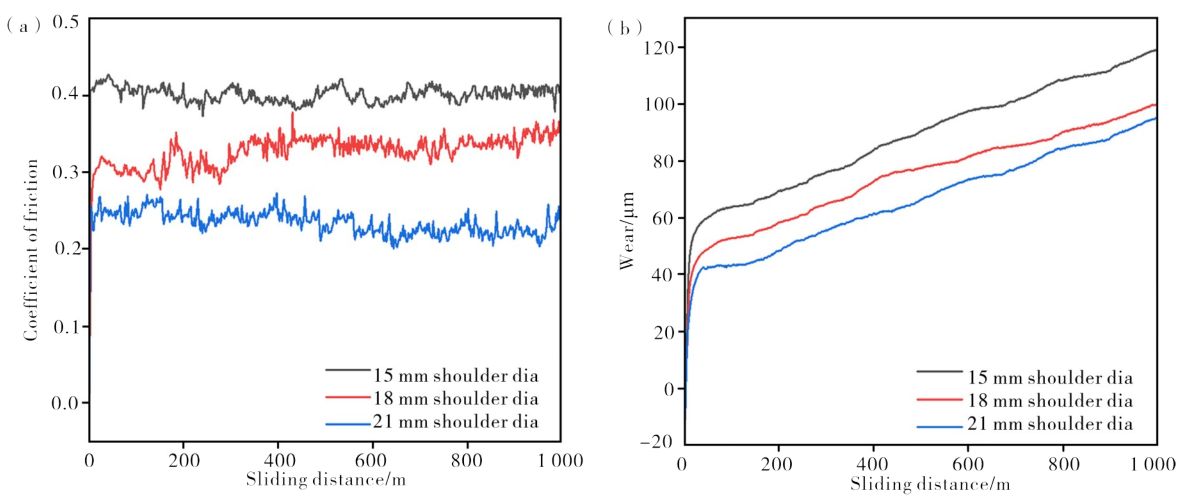
(a)—Al_2O_3[41];(b)—SiC[42];(c)—碳纤维[43];(d)—高熵合金[44];(e)—WC[45];(f)—TiC[46]。
(a)—Al_2O_3;(b)—SiC;(c)—carbon fiber;(d)—high-entropy alloy;(e)—WC;(f)—TiC.

图7 增强相种类[41-46]

Figure 7 Enhanced phase type schematic

左右,并且显微硬度提高了21.5%;与母材相比较,铝基复合材料的磨损率及摩擦系数分别降低了69.5%和63.45%。Mohammad[48]等同样以Al_2O_3作为增强相,复合材料的耐磨性能提高了30.12%,这是由于Al_2O_3分布均匀,使得材料具有一致的耐磨性能,同时Al_2O_3作为一种硬质陶瓷颗粒,能够有效抵抗滑动带来的材料磨损。Saravanakumar等[49]以SiC作为增强相制备铝基复合材料,该材料的磨损率达到了1.77 $mm^3 \cdot m^{-1}$,耐磨性能显著提高。Vasava[50]等通过添加SiC颗粒制备复合材料,并且利用搅拌头直径为21 mm的轴肩进行摩擦磨损试验,复合材料的平均摩擦系数约为0.25,小于母材的0.36,表明耐磨性能得到了提高(见图8)。

Megahed等[51]在6061铝合金中添加WC纳米颗粒(粒度约200 nm),合金硬度值达到144 VHN,较母材提高了39.81%,这是由于WC颗粒的添加改善材料的润湿性能,在摩擦磨损的过程中使材料的磨损量降低,耐磨性能得到提高。Moustafa[52]等通过对比hBN SiC、hBN NbC和hBN TaC杂化纳米颗粒(见图9(a)—(d))发现,这些颗粒阻碍了晶粒的生长,提高了材料硬度,以及提升了材料的自润滑效果。通过磨损试验发现:添加hBN TaC杂化纳米颗粒所制备的铝基复合材料的耐磨性能最好,其磨损率为6.66×10^{-6} $g \cdot s^{-1}$;添加hBN SiC和hBN NbC增强相的材料耐磨性能同样得到了提高,与母材相比,磨损率分别提高了31%和27%(见图9(e))。虽然

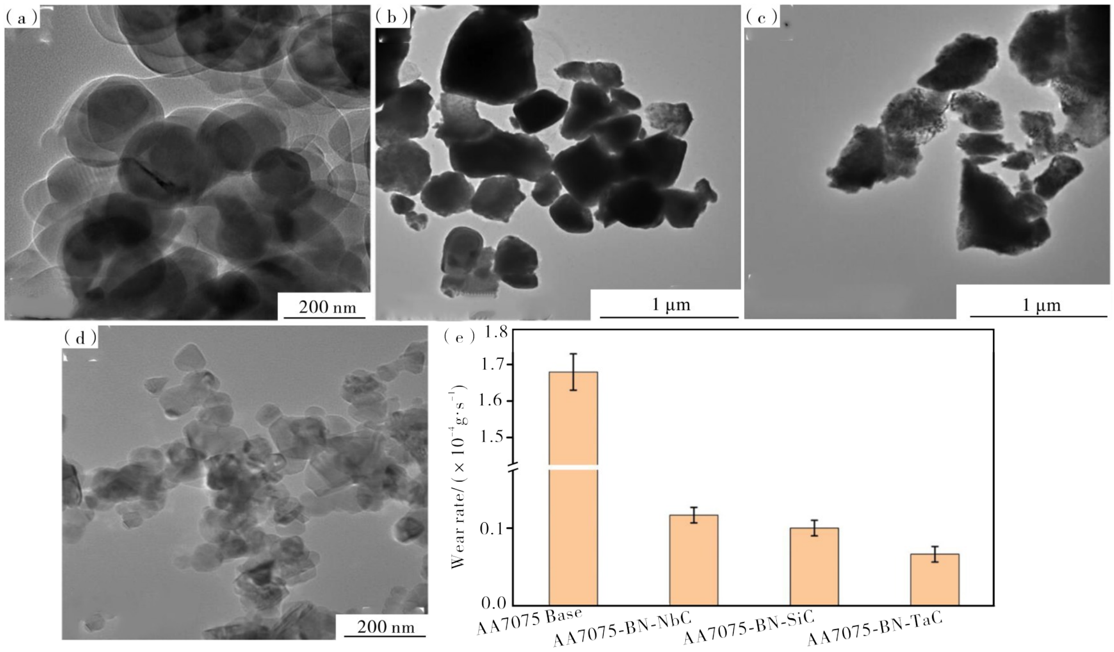


(a)—摩擦系数;(b)—磨损变化。
(a)—coefficient of friction;(b)—change in wear.

图8 摩擦磨损结果[50]

Figure 8 Friction wear results

采用搅拌摩擦加工工艺制备的铝基复合材料的耐磨性能得到提高，然而在制备的过程中仍然需要考虑增强相的含量。



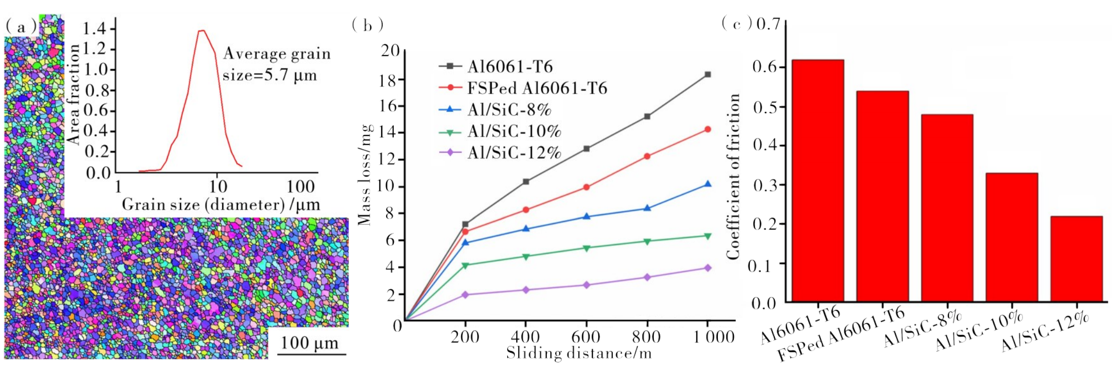
(a)—HBN；(b)—TaC；(c)—NbC；(d)—SiC；(e)—磨损率。
(a)—HBN；(b)—TaC；(c)—NbC；(d)—SiC；(e)—wear rate.

图9 铝基复合材料的TEM图及磨损率[52]

Figure 9 TEM image and wear rate of Aluminum matrix composite

4.2 增强相的含量

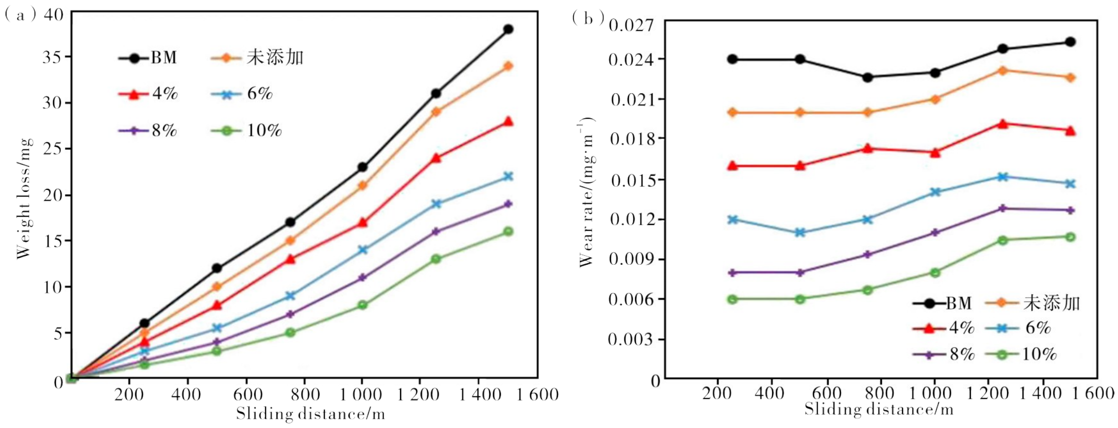
一般情况下，增强相含量越多复合材料的耐磨性能就越好。Ansari[53]等采用不同含量（质量分数分别为8%、10%和12%）的SiC颗粒制备复合材料，发现质量分数为12%的SiC复合材料平均晶粒尺寸达到了5.7 μm，同时其摩擦系数和磨损量也为最低（见图10）。添加硬质颗粒能有效地提高复合材料的耐磨性能[54]，增强颗粒含量增加会减少配合面之间的接触面积，因此耐磨性能显著提高。据文献[55-56]报道，对不同含量（质量分数5%、10%和15%）B_4C增强铝基复合材料的耐磨性能对比分析，结果发现：随着B_4C含量的增加，磨损率逐渐降低分别为2.4、2.1和1.8 $mm^3·Nm^{-1}$，但耐磨性能显著提高；当B_4C含量为15%时，耐磨性能最好。Abdelhady[57]等在相同的焊接参数下，制备了不同含量（质量分数4%、6%、8%和10%）的B_4C增强复合材料，结果发现磨损量和摩擦系数随B_4C含量的增加而逐渐减低（见图11），表明材料具有良好的耐磨性能。



(a)—Al/SiC-12%微观组织和平均晶粒尺寸；(b)—磨损量；(c)—摩擦系数。
(a)—Al/SiC-12% microstructure and average grain size；(b)—wear loss；(c)—coefficient of friction.

图10 铝基复合材料微观组织和磨损数据[53]

Figure 10 Aluminum matrix composite microstructure and wear data



(a)—磨损量;(b)—磨损率。

(a)—wear loss;(b)—wear rate.

图11 添加B_4C颗粒制备复合材料磨损数据[57]

Figure 11 Wear data of composites prepared by adding B_4C particles

然而,增强颗粒含量超过临界值时对耐磨性起到反作用。Abioye[58]等采用FSP制备复合材料,其中增强相含量分别为0.56、1.01和1.72 g,通过观察磨损过后的磨痕体积能够发现,当滑动距离为250 m左右时,随磨损体积增强相含量的增加而增加(见图12)。因此,使得复合材料的耐磨性能降低。增强颗粒含量通常是从低到高,当超过临界极限时复合材料容易形成缺陷,表现出较差的力学性能[59]。临界值不仅与增强相的含量有关,而且与母材、搅拌摩擦加工的工艺和搅拌头等因素均存在紧密的关系。

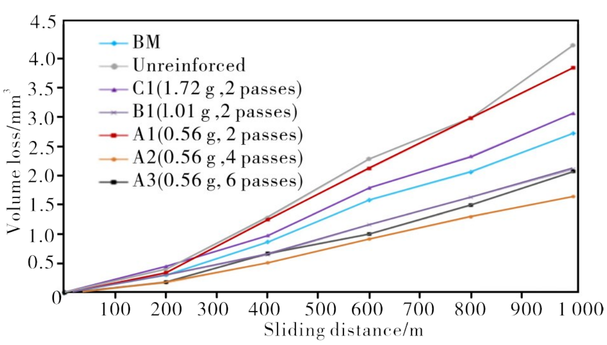


图12 磨损体积[58]

Figure 12 Wear volume

4.3 FSP制备工艺参数

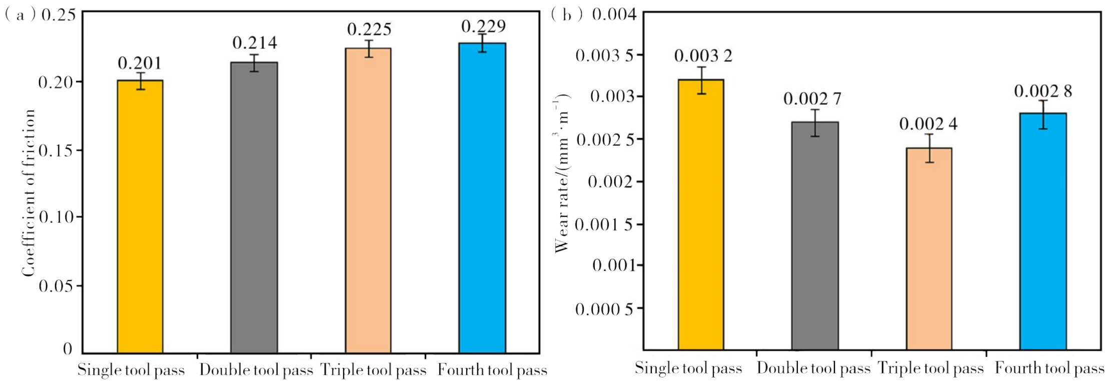
在焊接工艺方面,搅拌道次和焊接参数对焊缝的质量起到关键因素。增加搅拌道次有利于晶粒的细化,可有效提高材料的力学性能。同时,焊接参数产生的热输入量同样对焊缝的质量产生影响。但是,当焊接参数不适合时,热输入量不足或者热输入量过大,容易引发孔洞、或者飞边等缺陷,从而影响复合材料的耐磨性能。

4.3.1 搅拌道次

采用FSP制备复合材料时,在搅拌摩擦加工的作用下,母材产生的剧烈塑性变形将晶粒打碎,在冷却的过程中形成动态再结晶,同时第二增强相的引入也可有效的阻碍晶粒的长大。然而,通过多道次搅拌摩擦加工已经细化的晶粒会进一步减小,从而提高材料的耐磨性能。

Dwivedi[60]等引入了TiO_2纳米颗粒,通过4道次搅拌摩擦加工后发现,随搅拌道次的增加摩擦系数逐渐增加,但磨损率呈现出先下降后上升的趋势,3道次时磨损率最低达到了0.002 4 $mm^3·m^{-1}$(见图13),表明了材料耐磨性能不会随焊接道次的增加而提高。同时,通过观察磨损形貌能够发现,在摩擦磨损过程中3道次的复合材料增强颗粒不容易挤出(见图14)。Sangamaeswaran[61]等在制备铝基复合材料的过程中添加B_4C颗粒,进行多道次加工后发现,屈服强度的变化较平稳,但变化明显,且随加工道次的增加逐渐提高,在第3道次时显微硬度值达到最大为110 HV,在第2道次时摩擦系数的值最小达到0.393,表明硬度与磨损量成反比。

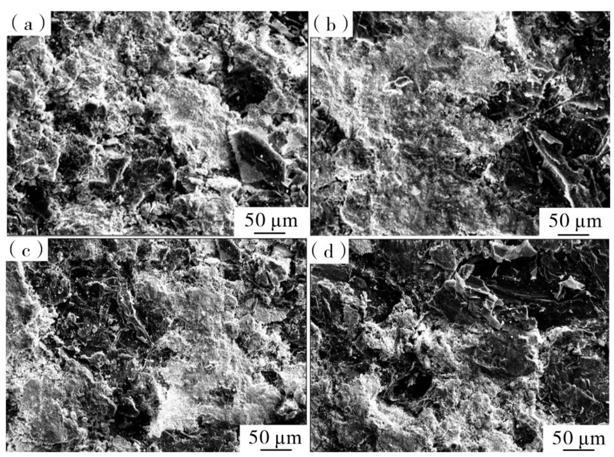
综上所述可知,增加搅拌道次同样有利于提高材料的耐磨性能,但在不同的焊接参数下增加搅拌道次,反而对材料产生反作用。因此,评估FSP焊接参数同样重要。



(a)—摩擦系数;(b)—磨损率。
(a)—coefficient of friction;(b)—wear rate.

图13 不同搅拌道次对摩擦磨损性能的影响[60]

Figure 13 Friction and wear data for different mixing passes



(a)—1道次;(b)—2道次;(c)—3道次;(d)—4道次。
(a)—one pass (b)—two passes;(c)—three passes;(d)—four passes.

图14 不同道次的磨损形貌[60]

Figure 14 Wear pattern of different passes

4.3.2 旋转速度

采用FSP制备复合材料时,通常采用较高的旋转速度。较低的转速产生的热输入量较低,会影响材料的流动性能,复合材料需要较大的热输入量才能获得高质量的性能[62]。Kaya[63]等以5083铝合金为母材制备复合材料,在相同质量分数的SiC颗粒和相同的焊接速度(20 mm·min^{-1})下制备复合材料,其中转速和轴向压力采用正交实验确定。结果表明:当旋转速度900 r·min^{-1}、轴向压力8 000 N时,磨损量、磨损率和摩擦系的数据占据优势,耐磨性能得到了提升;当轴向压力为6 000 N时,添加的增强相在基体中无法均匀地分布;而当轴向压力为10 000 N时,轴肩的下压量过大造成严重的飞边缺陷,引发了材料的耗损,并且过大轴向压力对颗粒的分布情况会造成负面影响。Saravanakumar[49]等采用低焊接速率和高移动速度的方法制备铝基复合材料(见图15),结果发现:当旋转速度在1 000 r·min^{-1}时磨损率达到1.77 mm^3·m^{-1},材料的平均晶粒尺寸为1.06 mm,材料表现出良好的耐磨性能;当旋转速度超过1 000 r·min^{-1}时,材料的耐磨性降低。

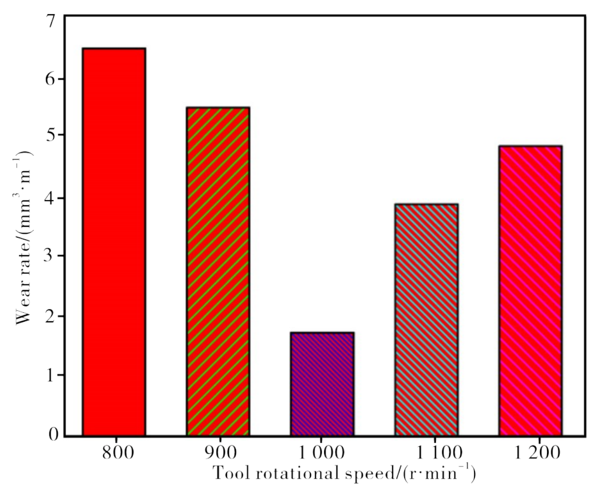


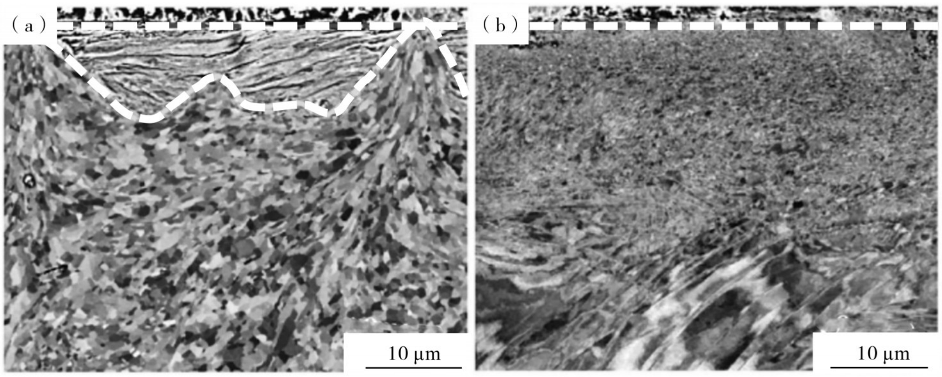
图15 不同旋转速度下复合材料磨损率[49]

Figure 15 Wear rate of composites at different rotational speeds

5 耐磨性提升机理分析

搅拌摩擦加工可提高铝基复合材料耐磨性能,因此对复合材料的耐磨性提升机理进行分析很有必要。在FSP往复滑动的过程中,动态再结晶(Dynamic recrystallization,DRX)的晶粒度被揭示为确定亚表面形态模式的关键参数。在焊接速度为30—50 mm·min^{-1}、移动速度为1 000—1 200 r·min^{-1}时,DRX尺寸的临界值约为0.5 μm。同时,随着增强相含量的提高,亚表面形态模式从漩涡特征变成层流特征[64](见图16)。在往复滑动过程中,磨损率普遍较高,这是因为产生了较厚的纳米混合层(即亚表面),且该表面容易产生裂纹[65],一旦开裂产生,后续就会引发裂纹的扩展和表面磨损的加剧,导致材料容易去除。同样,增强相含量较低时,亚表面形

态为漩涡模式;增强相含量较高时,亚表面形态为层流模式。这是由于增强相的含量较高,会增强晶界迁移的钉扎效应,在摩擦磨损过程中DRX晶粒的尺寸就会降低[65],从而导致磨损率降低。若DRX晶粒尺寸非常小时,导致塑性变形能力较差[66],耐磨性能就会变弱。因此,调控DRX晶粒的尺寸,对提升复合材料耐磨性具有一定的优势。



(a)—漩涡模式(增强相的质量分数0.3%);(b)—层流模式(增强相的质量分数2.2%)。
(a)—vertical mode (0.3% by mass of the reinforcement phase);(b)—laminar mode (2.2% by mass of the reinforcement phase).

图16 磨损后亚表面形态模式[64]

Figure 16 Sub-surface morphology pattern after wear

6 结论

(1)FSP制备铝基复合材料时,增强相的引入可提高材料耐磨性能。纳米级陶瓷颗粒对磨损性能起到关键的作用。但是,在FSP过程中纳米增强相易引发团聚的出现。因此,团聚现象将是影响铝基复合材料耐磨性能的关键因素之一,减少团聚也是未来研究的热点。

(2)变化不同的材料或者不同的增强相等因素,能够发现工艺参数并不是线性变化,而是一个范围。不同影响因素使用的工艺参数都会不同,因此制备复合材料过程中需要找到FSP合适的工艺窗口,以便提高铝基复合材料的耐磨性能。

(3)FSP制备的铝基复合材料,其耐磨性能不能快速提高,原因在于复合材料的机理尚未探明。想要科学解决FSP制备铝基复合材料耐磨性能的问题,需要对机理进行更加深入的研究,如增强相与基体的界面结合力、结合强度等。

参考文献:

[1] MIRJAVADI S S, ALIPOUR M, HAMOUDA A M S, et al. Effect of multi-pass friction stir processing on the microstructure, mechanical and wear properties of AA5083/ZrO_2 nanocomposites [J]. Journal of Alloys and Compounds, 2017, 726: 1262-1273.

[2] MOUSTAFA E B, MOSLEH A O. Effect of (TiB) modifier elements and FSP on 5052 aluminum alloy[J]. Journal of Alloys and Compounds, 2020, 823: 153745.

[3] PENG W, GAO Y, LI H, et al. Effects of different initial states on dynamic tensile properties and microstructure of 7075 aluminum alloy [J]. Materials Science and Engineering: A, 2024, 891: 145939.

[4] 关耀威,张宇洋,段伟,等.7075-T651铝合金摩擦磨损性能研究[J].材料研究与应用,2022,16(6):1046-1051.

[5] REN Q, YUE Z, SOYARSLAN C, et al. A coupled ductile damage model for metal matrix composites: Development and application[J]. Composites Part B: Engineering, 2024, 272: 111229.

[6] SINGH B, KUMAR I, SAXENA K K, et al. A future prospects and current scenario of aluminium metal matrix composites characteristics [J]. Alexandria Engineering Journal, 2023, 76: 1-17.

[7] SANKHLA A, PATEL K M. Metal matrix composites fabricated by stir casting process: A review [J]. Advances in Materials and Processing Technologies, 2022, 8(2): 1270-1291.

[8] SIVAKUMAR T, UDAGANI C, SIVARANJANI M, et al. Impact of BN and WC particulate reinforcements on mechanical properties and damage development of Al-2048 metal matrix composites [J/OL]. Advances in Materials Science and Engineering, 2022. https://doi.org/10.1155/2022/2286713.

[9] 罗潇,刘小冲,曾雨琪,等.陶瓷基复合材料构件内嵌孔加工工艺研究进展[J/OL].复合材料学报,2024:1-14. https://doi.org/10.13801/j.cnki.fhclxb.20240321.001.

[10] 吴晓晨,郑瑞晓,李露,等.SiC_f/SiC陶瓷基复合材料高温环境损伤原位监测研究进展[J].无机材料学报,2024, 39(6):609-622.

[11] HUANG J, LIU R, HU Q, et al. High temperature abradable sealing coating for SiCf/SiC ceramic matrix composites[J]. Ceramics International, 2023, 49(2):

1779-1790.

[12] ZHANG W, SHI F, WANG J, et al. Preparation and properties of a porous ZrO_2/SiZrBOC ceramic matrix composite with high temperature resistance and low thermal conductivity [J]. Journal of the European Ceramic Society, 2024, 44(4): 2329-2337.

[13] PARMAR H, TUCCI F, CARLONE P, et al. Metallisation of polymers and polymer matrix composites by cold spray: state of the art and research perspectives [J]. International Materials Reviews, 2022, 67(4): 385-409.

[14] 曹端兴,杨洋,陈新文,等.连续纤维增强聚合物基体复合材料多轴疲劳研究进展[J/OL].复合材料学报, 2024: 1-17. https://doi. org/10.13801/j. cnki. fhclxb.20231127.003.

[15] JIANG T, ZHANG W, SU Z, et al. Improving the wear resistance of 50 wt% Si particle-reinforced Al matrix composites treated by over-modification with a Cu-P modifier [J]. Tribology International, 2023, 180: 108247.

[16] YU Z, ZHENG K, LI X, et al. Effect of Ti_6Al_4V reinforcement particles on the mechanical, wear, and corrosion properties of AZ91D magnesium matrix composites [J]. Journal of Materials Research and Technology, 2023, 26: 7395-7411.

[17] MORTENSEN U A, RASMUSSEN S, MIKKELSEN L P, et al. The impact of the fiber volume fraction on the fatigue performance of glass fiber composites [J]. Composites Part A: Applied Science and Manufacturing, 2023, 169: 107493.

[18] 赫英杰.B_4C_p和APC混杂增强铝基复合材料制备及组织性能表征[D].哈尔滨:哈尔滨理工大学,2021.

[19] 杨朋军,李良,雷志强,等.SiC/Al铝基复合材料在惯性器件上的应用研究[J].导航定位与授时,2016,3(6):63-66.

[20] LI M, GUO Q, CHEN L, et al. Microstructure and properties of graphene nanoplatelets reinforced AZ91D matrix composites prepared by electromagnetic stirring casting [J]. Journal of Materials Research and Technology, 2022, 21: 4138-4150.

[21] SUN J, DING D, LIU W, et al. Strength and elastic modulus enhancement in Mg-Li-Al matrix composites reinforced by ex situ TiB_2 particles via stir casting[J/OL]. Journal of Magnesium and Alloys, 2022. https://doi.org/10.1016/j.jma.2022.09.020.

[22] AKBARPOUR M R, GAZANI F, MIRABAD H M, et al. Recent advances in processing, and mechanical, thermal and electrical properties of Cu-SiC metal matrix composites prepared by powder metallurgy[J]. Progress in Materials Science, 2023,140: 101191.

[23] SAJJADI S A, EZATPOUR H R, BEYGI H. Microstructure and mechanical properties of Al-Al_2O_3 micro and nano composites fabricated by stir casting [J]. Materials Science and Engineering: A, 2011, 528 (29-30): 8765-8771.

[24] 王浩伟.原位自生陶瓷颗粒增强铝基复合材料制备及应用[J].航空制造技术,2021,64(16):14-26.

[25] 于涛.混晶AA2024粉末冶金制备及挤压成形性能研究[D].哈尔滨:哈尔滨理工大学, 2023.

[26] MABUWA S, MSOMI V, NDUBE-TSOLEKILE N, et al. Status and progress on fabricating automotive-based aluminium metal matrix composites using FSP technique [J]. Materials Today: Proceedings, 2022, 56: 1648-1652.

[27] 罗锡才,刘灏霖,康利梅,等.搅拌摩擦加工方向对AZ61镁合金组织和力学性能的影响[J].材料研究与应用,2021,15(3):203-209.

[28] 李鹏,廉润康,马超群,等.加工道次对FSP制备高熵合金增强铝基复合材料组织和性能的影响[J].焊接学报,2022,43(6):11-19.

[29] ZHANG W, LU J, TAN L, et al. In vitro degradation and in vivo osteogenesis of Mg-Zn-Nd-Zr/HA composites prepared by friction stir processing[J/OL]. Journal of Magnesium and Alloys, 2023. https://doi.org/10.1016/j.jma.2023.09.030.

[30] DESAI V, BADHEKA V, ZALA A, et al. Fabrication of Al6061/Ti_3AlC_2 MAX phase surface composite by friction stir processing and investigation of wear properties[J]. Tribology International, 2024, 195: 109594.

[31] MEN J, PAIDAR M, ESLAMI-FARSANI R, et al. Investigation on microstructure, mechanical and tribological properties of friction stir processing of AZ31/AlFeCrMoNb surface composite [J]. Materials Chemistry and Physics, 2024,317: 129149.

[32] AKBARPOUR M R, MIRABAD H M, GAZANI F, et al. An overview of friction stir processing of Cu-SiC composites: microstructural, mechanical, tribological, and electrical properties [J]. Journal of Materials Research and Technology, 2023,27: 1317-1349.

[33] 王智,王文,张志娟,等.水下搅拌摩擦加工制备CoCrFeNiMn/6061Al复合材料组织和性能研究[J].塑性工程学报, 2023, 30(2): 223-230.

[34] 窦程亮,柳旭,黄晓猛,等.搅拌摩擦加工制备碳化硅铝复合材料性能及工艺的影响[J].航天制造技术, 2023(5): 34-38.

[35] ORŁOWSKA M, PIXNER F, HÜTTER A, et al. Manufacturing of coarse and ultrafine-grained aluminum matrix composites reinforced with Al_2O_3 nanoparticles via friction stir processing[J]. Journal of Manufacturing Processes, 2022, 80: 359-373.

[36] YELAMASETTI B, KUMAR P N, SAXENA K K, et al. Surface modification of aluminum alloy 6061 by embedding B_4C particles via friction stir processing[J]. Materials Research Express, 2022, 9(5): 56511.

[37] NATHAN S R, SUGANESWARAN K, KUMAR

S, et al. Investigations on microstructure, thermo-mechanical and tribological behavior of graphene oxide reinforced AA7075 surface composites developed via friction stir processing[J]. Journal of Manufacturing Processes, 2023, 90: 139-150.

[38] AZEVEDO C R F, MARQUES E R. Three-dimensional analysis of fracture, corrosion and wear surfaces[J]. Engineering Failure Analysis, 2010, 17(1): 286-300.

[39] ANSARI A J, BANSAL G, RIZVI S A H. Effect of reinforcement particles and multipass of friction stir processing on microstructure and mechanical properties of aluminium alloy[J]. Materials Letters, 2024, 355: 135555.

[40] KOLAGOTLA R K, KRISHNA B V, BHARGAVI P, et al. Toward achieving grain refinement in Al2014 alloy through multi-pass FSP: Microstructure and mechanical behavior[J/OL]. Journal of the Institution of Engineers (India): Series D, 2024: 1-10. https://doi.org/10.1007/s40033-024-00719-3.

[41] KUMAR A, SINGH V P, NIRALA A, et al. Influence of tool rotational speed on mechanical and corrosion behaviour of friction stir processed AZ31/Al_2O_3 nanocomposite[J]. Journal of Magnesium and Alloys, 2023, 11(7): 2585-2599.

[42] WANG Y, MONETTA T. Systematic study of preparation technology, microstructure characteristics and mechanical behaviors for SiC particle-reinforced metal matrix composites[J]. Journal of Materials Research and Technology, 2023,25:7470-7497.

[43] ZHONG K, ZHOU J, ZHAO C, et al. The effect of nickel coating on the mechanical properties and failure modes of continuous carbon fiber reinforced aluminum matrix composites[J]. Journal of Alloys and Compounds, 2022, 904: 164134.

[44] ZHU R, SUN Y, FENG J, et al. Effect of microstructure on mechanical properties of FeCoNiCrAl high entropy alloys particle reinforced Cu matrix surface composite prepared by FSP[J]. Journal of Materials Research and Technology, 2023, 27: 2695-2708.

[45] PATEL S K, SINGH V P, KUMAR D, et al. Microstructural, mechanical and wear behavior of A7075 surface composite reinforced with WC nanoparticle through friction stir processing[J]. Materials Science and Engineering: B, 2022, 276: 115476.

[46] GOLLA C B, BABAR PASHA M, RAO R N, et al. Influence of TiC particles on mechanical and tribological characteristics of advanced aluminium matrix composites fabricated through ultrasonic-assisted stir casting[J]. Crystals, 2023, 13(9): 1360.

[47] BHARTI S, GHETIYA N, PATEL K. Fabrication of AA6061/Al_2O_3 surface composite by double pass friction stir processing and investigation on mechanical and wear properties[J]. Advances in Materials and Processing Technologies, 2022, 8(sup3): 1785-1799.

[48] MOHAMMAD Q, GOPAL K, POORNIMA E, et al. Aluminum-alumina composite manufacturing: Unlocking potential with friction stir processing[J]. E3S Web of Conferences,EDP Sciences, 2024, 507: 1034.

[49] SARAVANAKUMAR S, PRAKASH K B, DINESH D, et al. Optimizing friction stir processing parameters for aluminium alloy 2024 reinforced with SiC particles: A Taguchi approach of investigation[J]. Journal of Materials Research and Technology, 2024, 30: 4847-4855.

[50] VASAVA A, SINGH D. Influence of shoulder diameter on hybrid surface composite of AA7075-T651/SiC/Graphene via friction sir processing [J/OL]. Materials Today: Proceedings, 2023. https://doi.org/10.1016/j.matpr.2023.04.626

[51] MEGAHED A A, MOHAMED M A, ABDEL HAMID M, et al. Microstructure, hardness, and wear properties of AA6061/WC nanocomposite fabricated by friction stir processing [J]. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 2022, 236(16): 9148-9156.

[52] MOUSTAFA E B, MIKHAYLOVSKAYA A V, TAHA M A, et al. Improvement of the microstructure and mechanical properties by hybridizing the surface of AA7075 by hexagonal boron nitride with carbide particles using the FSP process [J]. Journal of Materials Research and Technology, 2022, 17: 1986-1999.

[53] ANSARI A J, ANAS M. Effect of varying volume fraction of reinforcement on the microstructure, hardness and tribological behaviour of aluminium metal matrix composites developed through FSP technique [J/OL]. Journal of the Institution of Engineers (India): Series D, 2023: 1-11. https://doi. org/10.1007/s40033-023-00476-9.

[54] AKBARI M, ASADI P, ASIABARAKI H R. Investigation of wear and microstructural properties of A356/TiC composites fabricated by FSP[J]. Surface Review and Letters, 2022, 29(10): 2250130.

[55] BOOPATHI S. An investigation on friction stir processing of aluminum alloy-boron carbide surface composite [M]. Singapore: Springer Nature Singapore, 2022: 249-257.

[56] ABIOYE T E, ZUHAILAWATI H, ANASYIDA A S, et al. Enhancing the surface quality and tribomechanical properties of AA 6061-T6 friction stir welded joints reinforced with varying SiC contents[J].

Journal of Materials Engineering and Performance, 2021, 30(6): 4356-4369.

[57] ABDELHADY S S, ELBADAWI R E, ZOALFAKAR S H. Investigation of the microstructure, mechanical and wear performance of friction stir-processed AA6061-T6 plate reinforced with B_4C particles surface composite [J]. Journal of Composite Materials, 2023, 57(14): 2297-2310.

[58] ABIOYE T E, ZUHAILAWATI H, ANASYIDA A S, et al. Enhancing the surface quality and tribomechanical properties of AA 6061-T6 friction stir welded joints reinforced with varying SiC contents[J]. Journal of Materials Engineering and Performance, 2021, 30(6): 4356-4369.

[59] SHARMA V, TRIPATHI P K. Approaches to measure volume fraction of surface composites fabricated by friction stir processing: A review [J]. Measurement, 2022, 193: 110941.

[60] DWIVEDI S P, SHARMA S, LI C, et al. Effect of nano-TiO_2 particles addition on dissimilar AA2024 and AA2014 based composite developed by friction stir process technique [J]. Journal of Materials Research and Technology, 2023, 26: 1872-1881.

[61] SANGAMAESWARAN R, MUHILAN S, NAVIN J, et al. Mechanical and wear properties of friction stir processing AA 6082-T6/B_4C aluminium matrix composites [J/OL]. Materials Today: Proceedings, 2023. https://doi.org/10.1016/j.matpr.2023.05.112.

[62] KUMAR N, DAS A, PRASAD S B. An analysis of friction stir welding (FSW) of metal matrix composites (MMCs) [J]. Materials Today: Proceedings, 2020, 26: 2650-2656.

[63] KAYA N, ÇETINKAYA C, KARAKOÇ H, et al. Effect of process parameters of Al5083/SiC surface composites fabricated by FSP on microstructure, mechanical properties and wear behaviors[J]. Materials Chemistry and Physics, 2024, 315: 128991.

[64] ZHANG Q C, CHEN X, HAN Z. Subsurface morphological pattern, microstructure and wear response of Cu and Cu-Al alloys subjected to unidirectional and reciprocating sliding [J]. Wear, 2020, 462: 203521.

[65] CHEN X, HAN Z, LU K. Wear mechanism transition dominated by subsurface recrystallization structure in Cu-Al alloys[J]. Wear, 2014, 320: 41-50.

[66] CHEN X, HAN Z, LU K. Enhancing wear resistance of Cu-Al alloy by controlling subsurface dynamic recrystallization [J]. Scripta Materialia, 2015, 101: 76-79.

Research Progress on Stirring Friction Processing Technology and Wear Resistance of Aluminum Matrix Composites

LIU Aoxiang, WANG Jiangtao*, LI Xingchen, HE Mingtao, HU Kejun, XIE Li, LIU Chao, WANG Mingzhi

(Jiangsu University of Technology, Changzhou 213001, China)

Abstract: Aluminum matrix composites has the characteristics of low density, good processing performance, and corrosion resistance, which are very important in high-performance manufacturing and widely used in fields such as aerospace and marine machinery. However, under the working conditions of reciprocating motion, the wear phenomenon between structural components has the most significant impact on the material, thereby reducing the service life of the workpiece. Therefore, improving the wear resistance of workpieces and extending their service life are of great significance for expanding the scope of use of aluminum alloys. In the process of preparing aluminum matrix composites, friction stirring processing (Friction Stir Processing, FSP) technology is one of the emerging ways of preparing composites, with excellent microstructure, not easy to produce interfacial reaction and other characteristics, which provides a huge potential in the production of aluminum matrix composites. A review of the preparation of aluminum matrix composites by FSP is conducted, focusing on the types and contents of reinforcing phases, as well as the number of stirring passes and welding parameters in FSP, and discussing the effects of the above factors on the wear-resistant properties of aluminum matrix composites. Among the factors of reinforcing phase content, the more the content leads to poorer wear resistance of aluminum matrix composites; the increase of stirring passes is conducive to grain refinement, but when the degree of grain refinement is higher, it reduces the wear resistance of aluminum matrix composites. On this basis, the mechanism to improve the wear resistance is studied. Finally, the future research trends such as the need to solve the problem of agglomeration of nanoscale reinforced phases in the preparation of aluminum matrix composites by FSP and the selection of suitable process windows for FSP are summarized and outlooked.

Keywords: FSP; aluminum alloy; aluminum matrix composites; reinforcing phase types; reinforcing phase content; number of stirring passes; welding parameters; wear resistance

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