# 冷喷涂复合加工制造技术及其应用

# Cold spraying hybrid processing technology and its application

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**摘要：**冷喷涂是一种固态快速成形技术，现已用于增材制造、修复损伤的航空航天用零部件等。但冷喷涂沉积体的固有特性——高强低塑，限制了其工业应用。本文综述了冷喷涂复合加工技术的新进展及应用。重点讨论了冷喷涂可复合机械加工和喷丸等普通加工技术，也可与激光、热处理、热轧、热等静压、搅拌摩擦加工、搅拌摩擦焊和钎焊等热加工技术复合，提升冷喷涂沉积体的强塑性，以及冷喷涂层作为强化层促进有色金属的连接。最后指出冷喷涂与多种机械加工工序的协调、与焊接技术的复合等方面仍需加强，旨在复合其他技术来扩展传统加工制造的内涵。

**关键词：**冷喷涂；机械加工；喷丸；激光；搅拌摩擦焊；有色金属

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**Abstract：**Cold spraying(CS) is a solid-state rapid forming technology，and it has been used in additive manufacturing and repairing damaged aerospace parts. However，the inherent characteristic of cold sprayed deposits，*i. e.* high strength and low plasticity，limits its industrial applications. The new progress and application about cold spraying hybrid other processing technologies were reviewed in this paper，focusing on the following：cold spraying can not only hybridize with general manufacturing technologies，such as machining and shot peening，but also with the hot working and manufacturing technologies，such as laser，heat treatment，hot rolling，hot isostatic pressing，friction stir processing，friction stir welding and brazing，in order to improve the strength and plasticity of the cold sprayed deposits. The strength and plasticity of the cold sprayed deposits can be improved，and the coatings deposited by cold spraying can promote the weld of nonferrous metals. At last，it should be pointed out that further coordination of cold spraying with various machining processes and cold spraying hybrid welding technology needs to be paid more attention，aiming to expand the connotation of the conventional manufacturing.

**Key words：**cold spraying(CS)；machining；shot peening(SP)；laser；friction stir welding；nonferrous metal

20 世纪 80 年代中期，冷喷涂技术由 Papyrin 等研究者发现[1]，至今已得到长足发展。冷喷涂属于微型固态连接技术，微米级的颗粒在特制的收缩-扩张型 Laval 喷嘴内被高速气流加速，飞出喷嘴后以高速撞击基体，发生剧烈塑性变形而沉积到基体上，经过很多颗粒的沉积而形成涂层或块体[2-4]。采用的气体通常为一定压力的氮气($N_2$)、氦气(He)、压缩空气或其混合气体。与超音速火焰喷涂、电弧喷涂等热喷涂方法相比，冷喷涂层制备过程中温度较低，避免了金属氧化以及对基体不良的热作用[5-6]。因此，冷喷涂在制备易氧化的金属材料（铜及其合金[7]、铝及其合金[8-9]、钛及其合金[10-11]、钽[12]）以及温度敏感材料（纳米晶[13]、非晶材料[14-15]）具有较大优势。此外，还可以制备复合材料[16-17]、铜镍铟(CuNiIn)合金[18]、钴铬钼(CoCrMo)合

金[19]及高熵合金[20]等。迄今为止,冷喷涂拓展到增材制造(3D 打印)领域,称为“冷喷涂固态增材制造”,已制造出了溅射旋转靶材等简单的零部件[21-23]。同时,冷喷涂已用于修复受损伤的零部件(飞机蒙皮紧固件孔、直升机铝制桅杆、铸铁发动机),恢复其使用性能[4,24]。还有研究者尝试用其代替传统的熔焊技术进行有色金属的连接[25]。

然而,由于冷喷涂固有的沉积特性,即每个颗粒经过剧烈的塑性变形沉积形成涂层,导致冷喷涂沉积体塑性极差,限制其广泛的工业应用[26-27]。为了提高冷喷涂沉积体的塑性,一方面,探究冷喷涂沉积体塑性的影响因素,并进行工艺优化从而提高沉积体的塑性。为此国内外学者做了大量的研究,比如喷嘴尺寸优化[28-29],喷涂粉末种类的影响[30-31],气体种类、温度(250~1000℃)和压力(0.5~5MPa)的影响[32-34]以及基体表面状态的影响[35]等。Li 等[36]综述了颗粒的撞击行为,并采用模拟方法预测颗粒的临界速率。Yin 等[37]综述了冷喷涂过程中气流和颗粒加速行为及热交换机制。Assadi 等[26]综述了冷喷涂参数的影响及沉积特性。Lee 等[38-39]和 Luo 等[40]综述了结构演变和沉积特性。但是通过优化冷喷涂自身工艺改善沉积体的塑性是非常有限的。另一方面,通过复合其他加工制造工艺来促使冷喷涂沉积体强塑化,可引出很多新的复合加工制造技术,更加有利于冷喷涂技术的工业应用。

鉴于此,本工作提出“冷喷涂+”的概念,形成“冷喷涂+”复合加工制造技术,来提高沉积体的塑性。本文综述了现有的“冷喷涂+”复合加工制造技术:(1)冷喷涂复合机械加工和喷丸普通加工技术,用来制备复杂零部件,代替熔化焊直接连接异质有色金属。(2)冷喷涂复合热加工技术,比如激光、热处理、热轧、热等静压和搅拌摩擦加工,用来改善冷喷涂沉积体的强塑性;(3)冷喷涂复合搅拌摩擦焊和钎焊,冷喷涂涂层作为中间层连接有色金属材料,并作为强化涂层提高有色金属接头的强塑性,为加快冷喷涂工业化的应用提供理论基础。

## 1 冷喷涂+普通加工制造技术

### 1.1 机械加工

#### 1.1.1 制造零部件

传统的增材制造主要包括激光增材制造、电子束增材制造、电弧增材制造等,金属材料经过熔化-凝固过程制备零件,此过程中温度高于金属材料的熔点,容易造成金属材料的氧化和元素烧损[41-42]。冷喷涂属于固态增材制造技术,颗粒在冷喷过程中仅发生塑性变形,能够快速制备各种形状或结构比较复杂的零部件,并且零部件的物理、化学性质与原材料保持一致,避免了金属元素的烧损等冶金缺陷[4,43-44]。因此,冷喷涂不仅可以用于制造单一材料零部件,还可以制备复合材料零部件。

冷喷涂很容易制备出单一材料的零部件,且零部件的机械加工性优良,可以进行车、铣、刨、磨等机械加工。冷喷涂复合机械加工可以制备出 Cu 与 Al 的简单部件(块体、圆柱体、法兰等)以及功能部件(高磁场环境用的铜线圈组件)[45]。此外,冷喷涂还可制备复合材料零部件,两种及以上金属材料在零部件内部分布较均匀,比如复合材料法兰和 Zn-Al 大型旋转靶材,如图 1 所示[46]。美国陆军研究实验室成功制造出 Ni-Al 复合材料部件[24]。除此之外,冷喷涂可制备多层材料块材,材料在单一层内呈均匀分布,而层与层的材料不同,通过更换送粉器的粉末或采用多组元的送粉器来实现。多层结构可以是金属层-金属层(Ti 层-Al 层[47]),也可以是陶瓷层-陶瓷层($Al_2O_3$ 层-$ZrO_2$ 层[48]),甚至是金属层-陶瓷层。

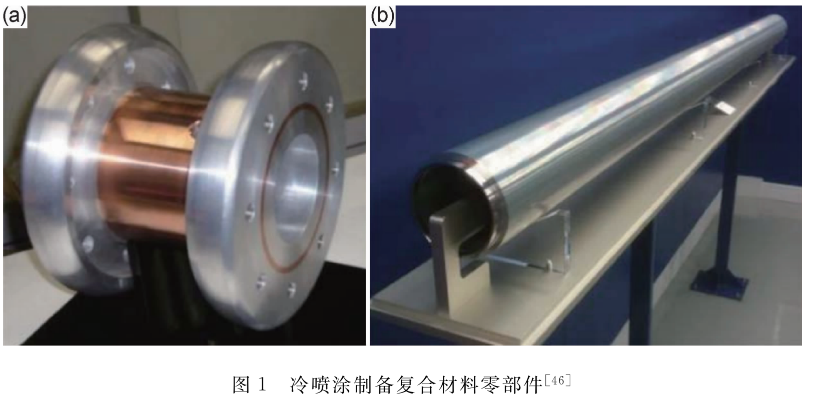


图 1 冷喷涂制备复合材料零部件[46]
(a)复合材料法兰;(b)Zn-Al 大型旋转靶材
Fig.1 Composite materials parts made by cold spraying[46]
(a)composite material flange;(b)Zn-Al large rotating target

随着现代科技的飞速发展,机械加工融合先进的数控技术,向高度集成化、智能制造方向发展。冷喷涂复合机械加工技术,建立大型的冷喷涂-数控机械加工平台,结合冷喷涂增材加工特性和传统减材加工的优势,制造具有理想的几何精度和表面特征的零部件,为制造业绿色化、智能化提供一个新的思路。冷喷涂的加法制造可以修正机械加工过程的超差错误,使受损的高价值部件得以再生和修复。提高部件的材料利用率,有利于机械加工过程的质量控制及制造复杂部件。迄今为止,德国(Hermle)五轴加工中心复合冷喷涂技术和五轴 CNC 加工技术已成功制备了多层金属沉积体,初步实现了功能/复杂零件快速加工制造的工业应用[49]。

1.1.2　直接连接(代替熔化焊)

有色金属(尤其是异质有色金属)的连接在汽车、航空航天等工业领域面临着挑战,受到国内外研究者的关注。传统的熔化焊因热输入大导致焊缝及其热影响区晶粒粗大,降低了接头的力学性能。采用热量集中程度高的热源来减少焊接过程中的热输入,比如用激光复合熔化极气体保护焊(MIG)来焊接异质有色金属:铝合金和镁合金[50],铝合金和不锈钢[51]等,用激光复合搅拌摩擦焊来焊接铝合金和镁合金[52]。冷喷涂复合机械加工直接连接有色金属,首先采用机械加工在基板上开一定形状的坡口,单边坡口(V 型和 U 型)或者双边坡口(X 型和双 U 型);然后用喷涂粉末作为填充材料,填满"焊缝"实现连接。同时,冷喷涂过程中的夯实效应促使焊缝附近的基板金属发生塑性变形引起晶粒细化,提高了接头的力学性能。并且通过选择喷涂粉末的成分实现焊缝区成分的调控,焊缝区内部为压应力,有利于制备较厚焊缝区实现厚板的连接[53]。美国陆军实验室已经申请了"冷喷涂工艺连接异质材料的方法"专利[54]。国外有学者尝试采用冷喷涂复合机械加工来连接铝合金。AA6061(3.25mm 厚)板材经过机械加工,两块板平对接呈 X 型坡口,用纯 Zn 粉末作为填充金属,采用冷喷涂工艺实现铝合金板的连接,接头金属微观组织内部没有明显的缺陷,Zn 沉积体和 AA6061 基体结合界面没有裂纹等缺陷,结合良好。铝合金接头的抗弯强度为 127MPa,根据弯曲的载荷-位移曲线,判断为脆性断裂,沿着铝合金 X 型坡口的尖端断裂,几乎没有塑性[55]。

## 1.2　喷丸

2003 年,西安交通大学 Li 等[56]发现冷喷涂过程中颗粒存在"夯实效应",纯 Ti 涂层的截面组织不均匀,靠近基体的组织致密,远离基体(接近涂层表面)的组织多孔。冷喷涂过程中后续的颗粒对已经沉积的颗粒进行夯实,类似喷丸的夯实效应,促使已经沉积的颗粒继续发生变形,组织变得致密。因此,利用喷丸技术可提高冷喷涂沉积体的致密性。

冷喷涂复合喷丸技术可分为三类:对基体进行喷丸处理后再冷喷涂称作"冷喷涂前喷丸",喷涂过程中粉末中混入喷丸颗粒称作"原位喷丸",以及对冷喷涂沉积体进行喷丸处理称作"冷喷涂后喷丸"。冷喷涂前喷丸和冷喷涂后喷丸可以提高基体的疲劳性能。对 AA6082 基板进行冷喷涂前和喷涂后喷丸处理,结果发现,喷涂前的喷丸更好地提升基体的疲劳性能,疲劳强度与喷涂态相比提升了 26%[57]。喷涂过程中原位喷丸辅助冷喷涂的原理示意图如图 2 所示[58]。首先,将粒径小的喷涂粉末颗粒和粒径大的喷丸颗粒均匀混合,以制备喷涂用粉末;然后,在冷喷涂过程中,大直径的喷丸颗粒夯实已经沉积的小直径颗粒,进一步提高颗粒的塑性变形程度,从而使沉积体致密化;最后速度低的大直径颗粒不能沉积(反弹)。西安交通大学的研究团队已经申请了相关专利[59],且系统研究了喷丸颗粒的直径、种类及与喷涂粉末的配比等对冷喷涂沉积体致密性的影响规律。例如,Ti 和 Ti-6Al-4V 喷涂粉末中加入不同比例的 1Cr13 丸体,采用冷喷涂制备 Ti 和 Ti-6Al-4V 沉积体。结果表明,随着丸体比例的增加,两种沉积体的孔隙率逐渐降低[60]。以 He 作为喷涂气体,冷喷涂(不加喷丸)制备 Ti 和 Ti-6Al-4V 沉积体作为参考,当丸体含量高于 50%(体积分数)时,Ti 和 Ti-6Al-4V 沉积体的维氏硬度高于同等条件氦气制备的沉积体[60]。

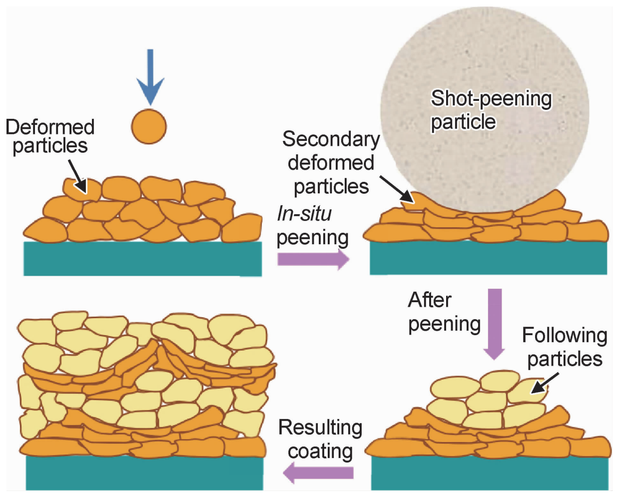


图 2　原位喷丸辅助冷喷涂的原理示意图[58]

Fig. 2　Illustration of *in-situ* shot-peening assisted cold spraying[58]

西安交通大学李成新等采用机械加工技术及原位喷丸辅助冷喷涂技术连接金属铝和铜,铝-铜异质接头制备过程示意图及实物图如图 3 所示[61]。在铝板和

铜板上通过机械加工开V型坡口，喷枪与坡口斜面成90°(图3(a)中①)，采用原位喷丸辅助冷喷涂在铝板和铜板上制备500μm厚的Al涂层(图3(a)中①和②)，然后喷枪恢复正常角度(与工件垂直)，喷涂纯Al粉末和丸体颗粒(不沉积)，直至填满整个V型坡口(图3(a)中③)，成功制备出铝-铜异质接头(图3(b))。铝-铜异质接头的抗拉强度约为71MPa，相当于Al基材抗拉强度的81%。

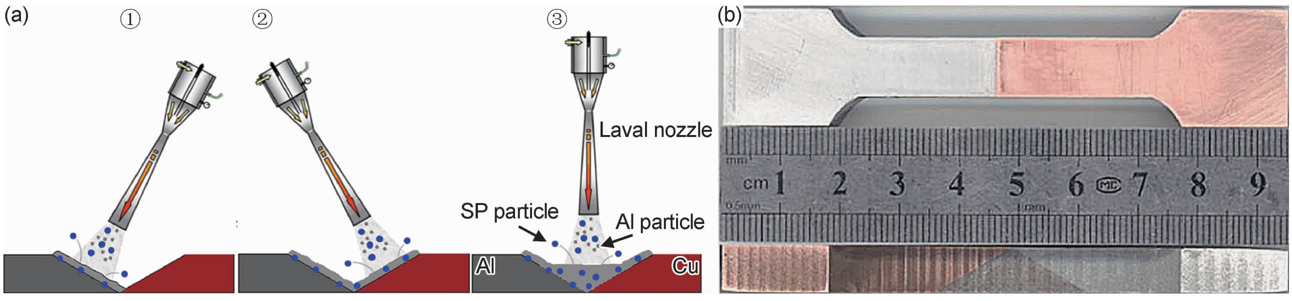


图3 原位喷丸辅助冷喷涂制备的铝-铜异质接头[61]
(a)制备过程示意图；(b)铝-铜异质接头实物图
Fig.3 Al-Cu dissimilar joint made by *in-situ* shot-peening assisted cold spraying[61]
(a)diagram of preparation process；(b)image of Al-Cu dissimilar joint sample

## 2 冷喷涂+热加工制造技术

在冷喷涂沉积体内部存在两类结合界面，一类是颗粒与基体的结合界面，是形成第一层的关键，主要影响沉积体与基体的结合强度；另一类是颗粒之间的结合界面，主要影响沉积体自身的内聚强度[62-63]。基体的材料特性(硬度、热学特性)及表面粗糙度会影响冷喷涂沉积体与基体的结合强度及沉积体自身的内聚强度[64]，粉末的材料特性也对冷喷涂沉积体的组织致密性和力学性能有影响。

冷喷涂Cu，Al，Ti-6Al-4V沉积体的内聚强度高，然而伸长率低，塑性差[24,64-65]。与基体的力学性能相比，沉积体与基体的结合强度较低。Cu，Al等颗粒硬度较低的冷喷涂沉积体，因冷喷涂过程中颗粒容易发生塑性变形，沉积体与基体的结合强度较高，在极端条件下(He，喷涂压力5MPa，喷涂温度727℃)，Cu沉积体与基体的结合强度可达200MPa[66]。然而高温合金、不锈钢、钛合金等颗粒硬度较高的冷喷涂沉积体与基体的结合强度偏低，例如，Ti-6Al-4V沉积体与Ti-6Al-4V基体的结合强度仅40MPa，即使采用He作为喷涂气体，其强度最多可达75MPa[30]。不同材料冷喷涂沉积体强度差异的原因在于：Cu，Al等颗粒在冷喷涂过程中容易发生塑性变形，促使沉积体内部组织致密，沉积体的力学性能优良。然而对于冷喷涂过程中难发生塑性变形的金属材料，沉积体内部孔隙多，界面结合不良，部分存在微裂纹，导致沉积体的力学性能下降。因此，通过冷喷涂与激光、热处理、热轧、热等静压、搅拌摩擦加工等热加工工艺的复合，来促使冷喷涂沉积体的组织致密化，改善强塑性，提高其力学性能。此外，冷喷涂工艺辅助搅拌摩擦焊和钎焊等热加工工艺来拓展冷喷涂的工业应用，为有色金属的连接提供了新的思路。

### 2.1 激光

近年来，激光增材制造(3D打印)逐渐发展起来[67-68]。激光复合冷喷涂技术可以结合二者的优点，制备出高强度的沉积体。激光可以通过三种不同的方法与冷喷涂工艺复合：(1)采用激光预先处理基体表面来增加基体的表面粗糙度，增强涂层与基体的结合强度；(2)激光原位辅助冷喷涂，增强涂层与基体的结合强度以及涂层的内聚强度；(3)对冷喷涂沉积体进行激光后处理，增强沉积体的耐蚀性和摩擦磨损性能等。

#### 2.1.1 基体表面预处理

为了提高冷喷涂沉积体和基体的结合强度，用激光对基体表面预处理，清理基体表面或者增加基体的粗糙度。例如，用激光在基体表面预制一定深度的盲孔，在表面形成阵列，随后冷喷涂粉末沉积在带有盲孔的基体上，填充盲孔并制备一定厚度的沉积体[40,69]。盲孔增加了沉积体和基体的接触面积，提高了沉积体和基体的结合强度[70]。

#### 2.1.2 激光原位辅助冷喷涂

激光原位辅助冷喷涂复合技术，是由英国剑桥大学的O'Neill等提出，随后国内浙江工业大学姚建华等也开始了该项技术的研究工作[71]。激光增材制造与激光原位辅助冷喷涂的区别在于：激光增材制造过程中温度高于材料的熔点，材料发生了熔化。然而激光原位辅助冷喷涂过程中，喷涂颗粒经过喷嘴加速后，

利用激光对高速的金属颗粒流和基体进行加热，且温度低于颗粒和基体材料的熔点，颗粒并没有熔化，但是发生软化和剧烈塑性变形，沉积到基体上形成组织致密的沉积体，提高了沉积体的内聚强度和与基体的结合强度[72-73]。Lupoi 等[74]采用激光原位辅助冷喷涂技术，在低碳钢管表面制备了 3mm 厚的纯钛涂层，涂层的孔隙率较低，且具有良好的机械加工性能。用 $N_2$ 作为冷喷涂气体，采用 300W 的激光和冷喷涂复合工艺制备 Ti-6Al-4V 沉积体，其内部组织的孔隙率低至 0.81%，颗粒间的界面结合良好，界面上生成了等轴晶；与之相比，采用 He 作为冷喷涂气体，相同的喷涂工艺制备的 Ti-6Al-4V 沉积体孔隙率为 2.1%[75]。采用激光对 Ti-6Al-4V 基体预热（基体温度为 120℃ 和 200℃），结合激光原位辅助冷喷涂复合技术制备 Ti-6Al-4V 沉积体，其中激光脉冲功率分别为 1.3J/cm$^2$ 和 2.2J/cm$^2$。Ti-6Al-4V 沉积体与基体的结合强度如图 4 所示[75]，经过激光预热基体以及激光原位辅助冷喷涂技术，可以显著提高沉积体与基体的结合强度，激光的热效应促进了基体和颗粒的热软化，增强了沉积体和基体的结合。

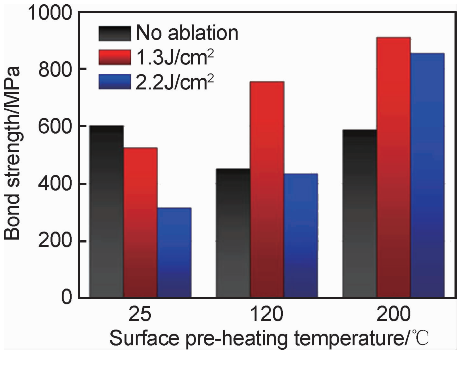


图 4　激光对冷喷涂 Ti-6Al-4V 沉积体与基体结合强度的影响[75]

Fig. 4　Effect of laser on adhesive strength of cold sprayed Ti-6Al-4V deposit and substrate[75]

#### 2.1.3　激光后处理

激光后处理可以改善冷喷涂沉积体的性能。激光对冷喷涂纯 Ti 沉积体表面处理后，在沉积体表面形成一层孔隙率低的屏障层[76]，提升了沉积体的耐蚀性，其耐蚀性与纯 Ti 基体相当[77]。有些学者通过热-力有限元模拟来探究激光后处理对基体的影响行为及演变规律[78]。采用模拟和实验相结合的方法可以更好地揭示激光后处理冷喷涂沉积体的强塑化机制：利用有限元来模拟激光处理过程中温度场的分布，并对激光处理后的沉积体组织进行表征，发现沿着表层到沉积体内部，组织可以分为三个部分：激光处理区，热影响区和沉积体。在激光处理区生成了钛氧化层，形成致密的屏障层[79]。热影响区包含两个区域：靠近激光处理区的片层粗晶区和细小等轴晶区，这是由于热影响区的温度高，促使晶粒发生了再结晶[80]。

### 2.2　热处理

冷喷涂沉积体内部结合界面存在一定程度的孔隙，降低了沉积体组织的致密性。对沉积体进行后热处理可以消除微小的孔隙或者孔洞，降低或消除残余应力，增强沉积体界面结合。对 Cu-4%Cr-2%Nb（原子分数）冷喷涂沉积体进行热处理，热处理后生成的 $Cr_2Nb$ 相在组织内均匀分布，促使组织弥散强化[81]。最近，Ren 等[82]采用 X 射线计算机断层扫描技术（CT）对冷喷涂沉积内部孔隙进行定量分析，并探究热处理前后孔隙大小和数目演变规律。结果表明，热处理有效减少孔隙的尺寸，并且一些细小的孔隙消失，然而大孔隙的数目没有减少，仅仅由不规则形状变得圆一些，面积变小[82]。后热处理可以提高冷喷涂沉积体的塑性，AA6061 冷喷涂沉积体经过去应力退火热处理和峰时效热处理后，强度和塑性明显提高[83]。

冷喷涂复合热处理技术还可以制备多孔的功能材料。例如，用于人体骨骼的多孔钛材料制备过程：纯镁和纯钛粉末均匀混合，然后采用冷喷涂制备 Mg-Ti 冷喷涂沉积体，对沉积体进行 1250℃ 的真空热处理，金属 Mg 由于蒸发而消失，形成了 Ti 的多孔组织，其压缩屈服强度与人体骨骼相当，可应用于医疗临床等领域[84]。

### 2.3　热轧和热等静压

热轧和热等静压加工工艺可以通过消除金属材料内部孔洞，细化和均匀化内部晶粒结构来消除材料内部缺陷，提高力学性能[85-87]。热等静压还可以优化固溶体相的分布，从而提高金属材料的高温力学性能[88]。为了提高冷喷涂沉积体的致密度和内聚强度，以及沉积体和基体界面的冶金结合，对冷喷涂沉积体进行热轧处理或者热等静压处理，消除冷喷涂沉积体结合界面以及沉积体与基体结合界面的孔洞，促进界面结合，提高沉积体的力学性能。304 不锈钢基体上的 Ti 冷喷涂沉积体经过热轧后处理（热轧温度为 850，950℃ 和 1050℃），随着热轧温度的升高，沉积体和基体结合界面上的孔隙得到消除，界面晶粒细化，结合强度得到提升[89]。对 $B_4C$/Al 复合材料冷喷涂沉积体（基体为 AA6061）进行不同热轧工艺处理，沉积体厚度减小到原来的 20%，40% 和 60%，沉积体与基体的结合强度得到显著提高[90]。Ti-6Al-4V 冷喷涂沉积体经过热等静压（温度 900℃，时间 2h，压力 103MPa）处理后，沉积体的孔隙率与冷喷态相比降低了 18%，几乎不存在孔隙[91]。

## 2.4 搅拌摩擦加工

搅拌摩擦加工是从搅拌摩擦焊演变而来的，可以用来细化材料晶粒，促使材料强塑化[92]。因此，搅拌摩擦加工可以用来改善冷喷涂沉积体的组织，并提高其力学性能。迄今为止，搅拌摩擦加工已经用来改善不同材料冷喷涂沉积体的力学性能，材料主要包括金属及合金材料（AA7075[93] 和 Cu-Zn 合金[94]），以及金属基复合材料（Ni-Ti 合金[95]、$Cr_3C_2$-NiCr[96] 和 Al-$Al_2O_3$[97]）等。

对冷喷涂沉积体进行搅拌摩擦加工，能够促使组织细化。EBSD 分析冷喷涂 Cu-Zn 沉积体发现，喷涂态的微观组织主要为 α 相，晶粒呈长条状，小角度晶界占的比例大，为 78.42%；经过搅拌摩擦加工，晶粒得以细化，甚至发现了孪晶界，发生了相变，由 α 相转变为 α，β″和 γ 的混合相，并且大角度晶界居多，为 90.47%[94]。搅拌摩擦加工过程中，在搅拌针的高速搅拌作用下，晶粒发生剧烈的塑性变形，促使强化相均匀化和晶粒细化，冷喷涂沉积体的组织趋于均一化，因此提高了冷喷涂沉积体的塑性。搅拌摩擦加工前后 AA2024/$Al_2O_3$ 冷喷涂金属复合材料沉积体的力学性能如图 5 所示。经过搅拌摩擦加工，沉积体的塑性得到明显提高，抗拉强度提高了 25.9%，伸长率提高了 27.4%[98]。

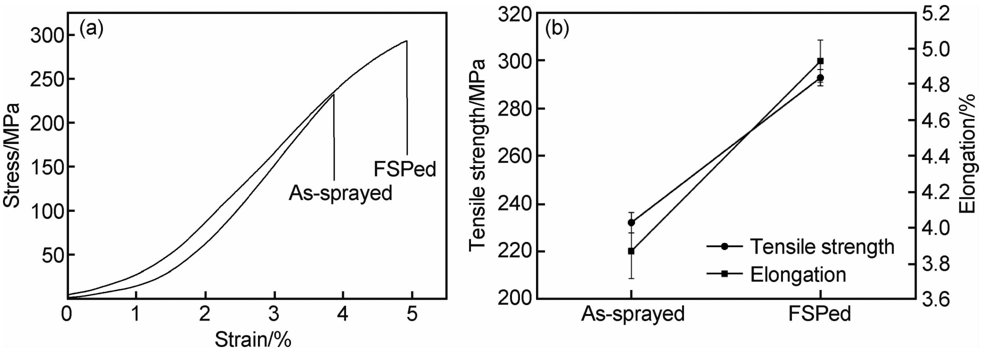


图 5 搅拌摩擦加工前后 AA2024/$Al_2O_3$ 冷喷涂沉积体的力学性能[98]

(a)应力-应变曲线；(b)抗拉强度和伸长率

Fig. 5 Mechanical properties of CSed AA2024/$Al_2O_3$ MMCs before and after friction stir processing[98]

(a)stress-strain curves; (b)tensile strength and elongation

## 2.5 搅拌摩擦焊

与熔化焊接头相比，搅拌摩擦焊接头的力学性能更高，具有很大优势[99-100]。然而部分异质搅拌摩擦焊接头的界面可能生成了金属间化合物，并存在软化区，降低了接头的塑性。同时，搅拌摩擦焊接过程中，由于搅拌工具轴肩下压，导致焊缝区域凹陷，低于板材平面，降低了接头的使用性能（比如耐蚀性和耐磨性等）。冷喷涂复合搅拌摩擦焊有两种形式：(1)冷喷涂层作为中间层，来阻止金属间化合物的生成；(2)采用冷喷涂对接头进行修正，填充接头的凹坑，并改善接头的使用性能。

### 2.5.1 冷喷涂层作为中间层

采用冷喷涂制备中间过渡层、复合搅拌摩擦焊技术连接异质有色金属，可以有效防止金属间化合物的生成，提高接头的塑性。例如，镁合金和铝合金的连接，首先在 ZE41A 镁合金端面采用冷喷涂技术制备 AA6061 过渡层，然后对带有纯铝过渡层的 ZE41A 镁合金和铸造 AA6061 铝合金进行搅拌摩擦焊，形成良好的 AA6061/AA6061 层/ZE41A 搅拌摩擦焊接接头[101]。AA6061 过渡层阻碍了镁合金和铝合金的直接连接，避免生成金属间化合物，改善了接头的组织，接头抗拉强度达到 315MPa，高于 ZE41A 镁合金，与铸造 AA6061 铝合金相当。采用冷喷 Al 沉积体作为中间层（约 200μm），对 AA6022 和高强钢进行搅拌摩擦搭接焊，形成了牢固的接头。接头分为三个区域：焊缝区，界面区和钢侧的热影响区，冷喷涂 Al 中间层有效地阻碍了 Al/Fe 界面上金属间化合物的生成[102]。

### 2.5.2 摩擦焊接头强化及防护

采用冷喷涂工艺对搅拌摩擦焊接头表面弧纹凹陷区域进行修复，可以恢复接头的完整性，强化接头力学性能的同时提升接头防护功能。Al-20%$Al_2O_3$（体积分数）复合材料冷喷涂涂层完全覆盖在 AA2024-T3 搅拌摩擦焊接头上，改善了接头力学性能和耐蚀性等[103]。冷喷涂前后铝合金搅拌摩擦焊接头的力学性能如图 6 所示。与焊态相比，搅拌摩擦焊接头经过冷喷涂涂层修正凹陷区域后，其强度和伸长率明显提升[104]。接头得以强化的原因在于：冷喷涂过程中存在两种效应，一种是喷丸效应（shot peening effect，SPE)，一种是热气效应（heat flow effect，HFE）。喷

丸效应是高速的颗粒撞击到基体上产生剧烈的塑性变形，细化晶粒，在涂层和焊缝内部形成压应力，提升了接头的强度。热气效应是冷喷涂过程中高温的气流对基体以及颗粒进行加热，促使颗粒软化更好地产生塑性变形，结合界面发生了再结晶，促进了涂层和搅拌摩擦焊表层的结合。这两种作用不是简单叠加，而是协同作用，共同提高了接头的强度[105]。此外，冷喷涂还可以降低搅拌摩擦焊接头的残余应力，提升其耐蚀性。腐蚀始于晶界并沿着晶界扩展，细化的晶粒促使晶界变曲折且数目增多，提升了接头的耐蚀性[105-106]。

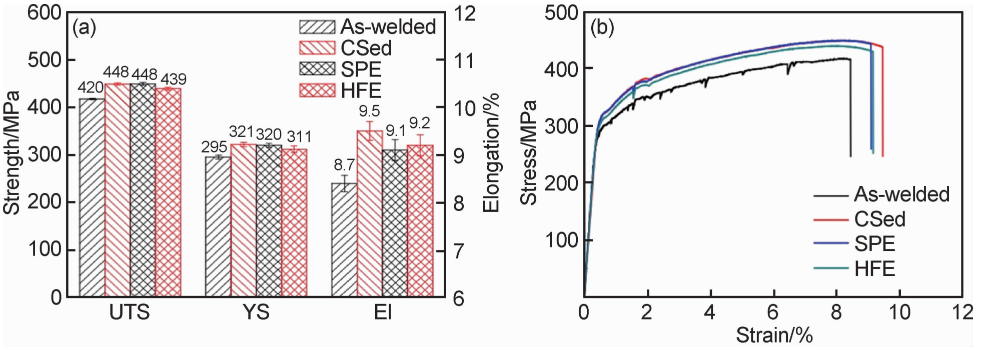


图 6 冷喷涂前后铝合金搅拌摩擦焊接头的力学性能[104]
(a)抗拉强度，屈服强度和伸长率；(b)应力-应变曲线
Fig. 6 Mechanical properties of friction stir welding joint of aluminum alloy before and after cold spraying[104]
(a)tensile strength, yield strength and elongation; (b)stress-strain curves

## 2.6 钎焊

钎焊是通过钎料熔化润湿母材，填充焊缝而实现连接的。钎焊接头的结合界面上生成金属间化合物，且存在孔洞和裂纹等缺陷，降低了接头的强度[107]。采用冷喷涂辅助钎焊，用冷喷涂层做钎料层，钎料在母材上可以均匀铺展，并且有效防止钎料和母材氧化，从而改善钎焊接头组织，提高其力学性能。

采用冷喷涂辅助钎焊可以改善异质金属钎焊接头组织，提高其力学性能。聂海杰等[108]采用冷喷涂工艺，在 AZ31B 镁合金的待焊面制备 90μm 的纯铜涂层，采用室温进行喷涂实验，可以有效防止镁合金氧化。然后打磨纯铜涂层至 50μm 厚，与 08F 钢进行钎焊实验，钎焊温度为 530℃，保温时间为 60min。钎缝中生成了 Mg-Cu-Al 三元相，在镁合金侧还分布着 $Mg_2Cu$ 共晶相；在 08F 钢侧，Mg-Cu-Al 三元相镶嵌在网状连续的 $Mg_2Cu$ 二元共晶相中，起到钉扎作用，提升了钎焊接头的强度。何培龙等[109]以 Zn (95%，质量分数)粉末和固态钎剂 CsF-$AlF_3$(5%)混合物为喷涂粉末，采用氮气作为工作气体，在喷涂温度 330℃ 和压力 2.1MPa 的冷喷涂条件下，在 AA5083 母材上制备纯锌涂层，实现了 AA5083 母材的钎焊连接。涂层对母材表面防护，阻止了复杂氧化膜的生成，纯锌钎缝与母材界面达到冶金结合[109]。

## 3 结束语

冷喷涂复合传统的普通加工制造技术和热加工技术，提升冷喷涂沉积体的致密度及塑性；复合搅拌摩擦焊和钎焊等加工工艺，提高了有色金属接头的强度。复合技术潜在的应用范围将涉及航空、航天等更多领域。

冷喷涂制备块材、复杂零部件以及复合其他加工制造技术尚存在一些关键问题亟待解决：(1)在冷喷涂和机械加工复合时，如何通过计算机编程控制喷枪移动轨迹来制造复杂零部件，并根据零部件的尺寸大小及厚度反馈调节喷涂工艺参数，以及冷喷涂工艺与多种机械加工工序的协调仍是需要解决的问题，在增材制造及零部件修复等领域仍然有较长的路要走；(2)冷喷涂沉积体的塑性较差，通过复合喷丸、激光、热处理及搅拌摩擦加工等工艺，其强塑性与母材相比仍然比较低，良好的强塑性仍旧是需要解决的难题；(3)冷喷涂与焊接技术的复合，旨在提高同质、异质金属的接头强度，改善接头软化问题；(4)冷喷涂向其他加工领域的扩展，例如冷喷涂涂层的压应力特性可以提高基体的疲劳寿命；冷喷涂还可用于干法刻蚀，即采用冷喷涂进行喷粉加工基体(减法制造)，来代替传统的喷粉微加工技术，例如基体微型通孔的加工。

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