铜基自润滑电接触复合材料研究综述

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摘 要：铜基自润滑复合材料因其优异的机械强度、良好的导电导热性能及自润滑特性,常被用于制备电刷、受电弓滑板等滑动电接触元件。从摩擦接触界面固体润滑膜形成的角度,详细叙述了铜基自润滑复合材料的润滑机理,指出摩擦接触界面固体润滑膜有效阻止了摩擦副对磨表面间的直接接触,使摩擦主要发生在固体润滑膜的内部,是铜基自润滑复合材料具备减摩自润滑特性的主要原因。同时对铜基自润滑复合材料的电磨损机制进行了详细介绍,指出铜基自润滑复合材料在滑动电接触过程中的磨损机制主要有磨粒磨损、粘着磨损、剥层磨损和氧化磨损四种,并从作用机制和形貌特征角度对它们进行了详细分析。最后,提出了铜基自润滑电接触复合材料研究领域目前存在的问题,并展望了相应的研究方向。

关键词：铜；复合材料；电接触；自润滑；磨损机制
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Review on Research of Cu-based Self-lubricating Electrical Contact Composites

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ABSTRACT: Cu-based self-lubricating composites are the most widely used sliding electrical contact materials due to their superior combined properties of high mechanical strength, excellent electrical and thermal conductivities and self-lubricating property. In this paper, the lubricating mechanism of Cu-based self-lubricating composites was reviewed based on the formation process of solid-lubricating film at the tribo-interface and it was commented that this solid-lubricating film is responsible for the good wear performance of Cu-based self-lubricating composites by preventing the direct contact between the frictional surfaces. Meanwhile, the electrical wear mechanisms of Cu-based self-lubricating composites were introduced and it was indicated that abrasive wear, adhesive wear, delamination wear and oxidation wear are the dominant wear mechanisms of Cu-based self-lubricating composites during sliding electrical contact. Finally, the currently existing problems in the field of Cu-based self-lubricating electrical contact composites and corresponding research directions were put forward.

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KEY WORDS: Cu; composites; electrical contact; self-lubricating; wear mechanisms

滑动电接触元件的功能是在设备的固定部件和运动部件之间传导电流,其性能优劣直接影响设备的正常运转[1—3]。滑动电磨损是接触元件在通电状态下的摩擦磨损行为[4—5]。与普通机械摩擦磨损相比,带电条件下的摩擦磨损过程要复杂得多,它既受到机械因素的制约,又受到电流热效应的影响,同时还被工况环境所影响[6—8]。滑动电接触界面因摩擦作用和电流热效应所释放的大量热量,会产生高温,从而导致材料耐磨性能降低,磨损加剧[9—10]。理想的滑动电接触材料既要具备良好的减摩耐磨性能,又要具备优异的电接触性能[11—13]。自润滑复合材料能够有效地解决滑动接触界面电流收缩及耐磨性的问题,被认为是最理想的滑动电接触材料[14—15]。传统铜基自润滑复合材料兼具铜基体优异的机械强度、良好的导电导热性能以及固体润滑剂的自润滑特性,是一种典型的滑动电接触材料,被广泛用于制造电刷、受电弓滑板等滑动电接触元件[16—18]。

1　铜基自润滑复合材料的润滑机理

铜基自润滑复合材料的润滑减摩机理是,其内部包含的固体润滑剂颗粒能在摩擦副的接触表面间聚集铺展开,形成一层剪切强度较低的固体自润滑膜,这层固体润滑膜能有效阻止对磨表面间的直接接触,使摩擦主要发生在固体润滑膜的内部,从而达到减小摩擦、降低磨损的目的[19—22]。铜基自润滑复合材料与对偶材料发生摩擦时,二者摩擦表面间固体润滑膜的形成原理如图1所示[23]。在摩擦开始之前,复合材料待磨表面的组成结构与材料内部基本一样,即由铜基体和固体润滑剂颗粒组成,固体润滑剂颗粒均匀分布在铜基体中,如图1a所示。在摩擦初始阶段,摩擦副之间主要是铜基体和对偶材料之间的直接接触,摩擦比较剧烈,摩擦副运动状态不太稳定,随后复合材料的摩擦表面受到挤压而发生变形,并释放大量摩擦热,此时处于复合材料表层的固体润滑剂颗粒在挤压变形和摩擦热的共同作用下逐渐向外表面挤出,从而复合材料外表面固体润滑剂的含量增加,固体润滑剂裸露在复合材料的摩擦表面上,如图1b所示。固体润滑剂一般是剪切强度较低的物质,或者在载荷和摩擦热的共同作用下能够形成剪切强度较低的物质。这些剪切强度较低的物质逐渐在摩擦副的接触界面聚集,并在切向摩擦力的作用下被剪切摊开在摩擦表面上。初始阶段挤出的固体润滑剂颗粒不充足,形成的固体润滑膜在摩擦表面上的覆盖面积较小,此时材料的摩擦系数和磨损率比较高。随着摩擦时间的延长,向摩擦表面挤出的固体润滑剂颗粒不断增多,摩擦副反复摩擦与压制的作用使固体润滑膜不断得以补充和完善,最终在材料表面形成一层较为连续完整的固体润滑膜,如图1c所示。铜基自润滑复合材料的润滑减摩效果基本依赖于摩擦接触界面固体润滑膜的完整程度。如果润滑膜的形成和磨耗处于相对平衡,则润滑状况良好;如果润滑膜的形成速率跟不上磨耗速率,则润滑失效,磨损加剧[24]。

2　铜基自润滑复合材料的电磨损机理

滑动电磨损过程中常出现磨粒磨损、粘着磨损、表面疲劳磨损、氧化磨损四种形式的磨损[17,25—28]。实际滑动电磨损过程中,一般是几种磨损机制同时存在,而且一种磨损的发生常常会引发其他形式的磨损。随着实际工况条件的变化,不同形式磨损机制的主次不同。

磨粒磨损是最常见的一种磨损形式,它是指对磨表面上的硬质微凸体以及接触界面硬质颗粒在摩擦

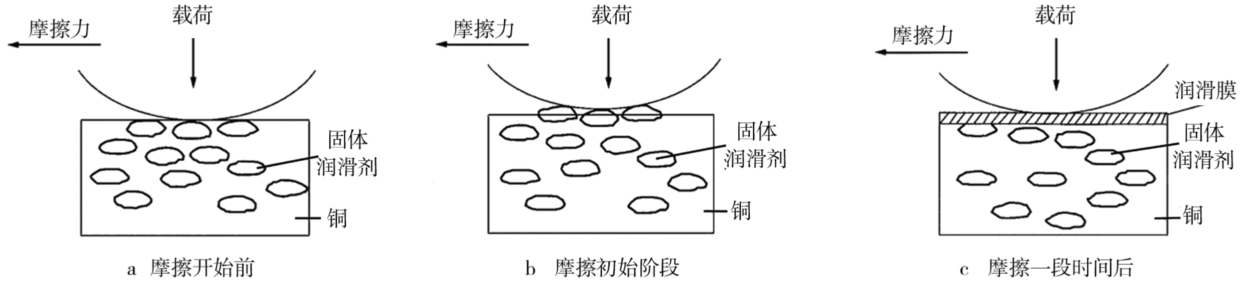


图1　固体润滑膜形成原理[23]

Fig.1 Formation mechanism of solid-lubricating film

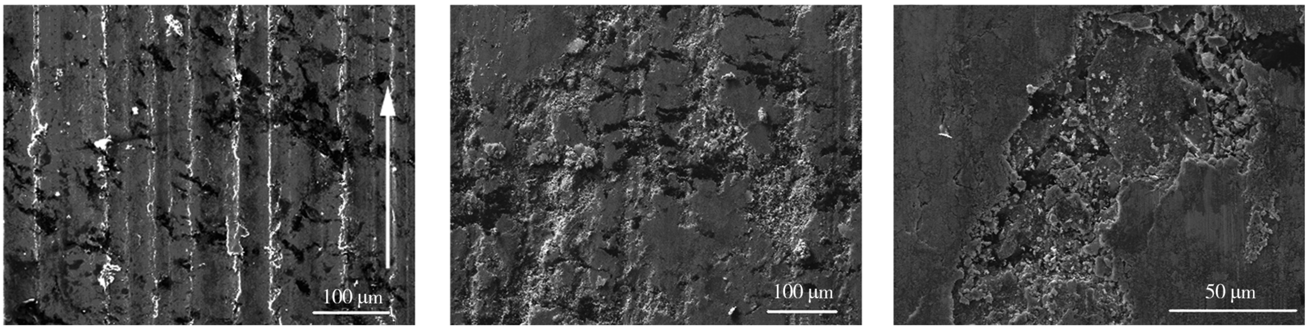
副相对滑动过程中割裂物体表面,从而引发表层材料损伤或脱落的现象。为了保护换向器滑环、接触网导线等对偶件表面免受损伤,一般滑动电接触材料的硬度都较低,在滑动电磨损过程中,对偶件表面的硬质微凸体以及摩擦界面的硬质磨屑容易在外加载荷的作用下被压入滑动电接触材料表层,造成磨粒磨损。图 2a 为铜基自润滑复合材料的电磨损表面磨粒磨损形貌,可以看出,电磨损表面沿滑动方向有明显犁削造成的擦伤或沟槽。

固体表面微观不平,因此摩擦副之间只在一些离散分布的微凸体顶峰发生接触。当接触表面间发生相对滑动时,由于粘着效应而形成的粘着结点将在相对滑动和载荷的共同作用下发生剪切断裂,造成表层材料或以磨屑的形式脱落,或在摩擦表面间发生转移,此类磨损形式称为粘着磨损。在滑动电磨损过程中,一方面,如果表面润滑膜不够连续完整,就容易造成摩擦表面间金属与金属的直接接触,从而诱发粘着磨损中以塑性变形为起因的第一类胶合;另一方面,由于摩擦作用和电能损耗释放大量的热量,使摩擦接触界面温度升高,从而诱发第二类胶合。图 2b 为铜基自润滑复合材料的电磨损表面粘着磨损形貌,可以看出,电磨损表面有明显粘着磨损造成的材料转移痕迹。

表面疲劳磨损是指当摩擦表面实际接触区域形成的循环应力超过局部表层材料的疲劳强度时,引发材料表层萌生裂纹并逐步扩展,当裂纹连成一体时,造成表层材料剥落的现象。滑动电磨损过程中,固体润滑膜的局部破损属于表面疲劳过程中的剥层磨损。固体润滑膜在接触应力的反复作用下,首先在薄弱部位萌生微裂纹,随后微裂纹逐渐向表层内部及四周扩展,当裂纹扩展并连成一体时,就导致局部固体润滑膜呈薄片状从表层剥落(图 2c)。

在滑动电磨损过程中,摩擦作用和电流热效应造成摩擦界面升温,一方面会使摩擦副的表层材料发生氧化而形成一层氧化膜,氧化膜的存在会增加摩擦表面间的接触电阻,从而阻碍电流的传导,并导致摩擦界面温度进一步升高,使磨损加剧;另一方面会促进表面润滑膜中固体润滑剂的氧化,使材料表面摩擦层内部颗粒间的结合力减弱,从而降低表面润滑膜的减摩润滑性能,并在接触压力和切向摩擦力的作用下造成润滑膜局部脱落。因此,氧化磨损也是铜基自润滑电接触复合材料的一种重要磨损机制。

铜基自润滑复合材料的摩擦磨损性能受材料组成、载荷、速度、工况条件等很多因素的影响,对于一定的复合材料体系在不同的工况条件下及不同的磨损阶段,这四种磨损机制会相互转换,并以其中一种或几种机制为主导。



a　磨粒磨损形貌　　b　粘着磨损形貌　　c　剥层磨损形貌

图 2　铜基自润滑复合材料的电磨损表面形貌(箭头指示滑动方向)[29]

Fig. 2 Worn surfaces of the Cu-based self-lubricating composites with current (the arrow indicates the sliding direction)

3　存在的问题

近年来,铜基自润滑电接触复合材料的性能不断提高,其应用范围也不断扩展,但在制备与应用中仍然存在以下几个方面的问题亟待解决:

1) 铜基自润滑复合材料主要依靠铜基体提供一定的机械强度并改善材料的导电导热性能,依靠固体润滑剂的减摩、自润滑特性来提高材料的磨损抗力。铜基体含量增多在提升强度和导电导热性能的同时,会削弱材料的磨损抗力;而固体润滑剂含量增多在提升减摩润滑性能的同时,会导致材料强度和导电导热性能降低。因此,想提高铜基自润滑复合材料的滑动电接触性能变得越来越困难。然而随着现代工业的快速发展,各类电机、仪表朝着高速高载化方向发展,滑动电接触元件的磨损速率加快,使用寿命缩短,传统铜基自润滑复合材料已难以满足目前的需求,因此

迫切需要开发新型高性能滑动电接触材料[29]。

2）随着航空航天工业的快速发展，对应用于高空环境中的新型高性能滑动电接触材料的需求越来越迫切。即便是在高真空环境中运转的航空设备，其在组装、地面调试或发射的过程中也会受到潮湿空气的影响，而近地轨道上的航空设备在运转过程中会一直接触到游离的氧原子[30—31]，因此运用在航空航天设备上的滑动电接触元件需要能够适应外部环境的变化。然而，每一种固体润滑剂都有其自身的适用范围，在一个环境中表现优异的固体润滑剂往往不能在另一个环境中提供很好的润滑，所以传统的单润滑剂铜基自润滑复合材料并不能满足上述要求，开发能够适应从大气环境到高空环境变化的新型滑动电接触材料势在必行。

3）滑动电接触元件在通电运行条件下的磨损由机械磨损、电磨损以及电弧侵蚀三部分组成[32]。载流过大以及因速度过快或压力不足导致的摩擦表面接触不稳等因素都有可能引起火花烧损现象。电弧产生的瞬间高温会烧伤接触表面，导致剧烈磨损，此时电弧烧损成为材料整个磨损中的重要部分[33—35]。目前电磨损过程中电弧对材料的烧蚀机理尚未弄清，研究铜基自润滑复合材料的抗电弧烧蚀性能对其滑动电磨损性能的提升有着非常重要的现实意义。

4 研究方向

针对上述铜基自润滑电接触复合材料领域目前存在的问题，通过基体合金化、表面石墨镀覆以及改善制备工艺等方法已经很难从根本上有效提升铜基自润滑复合材料的滑动电磨损性能，笔者认为在以后的研究中可以从以下三个方面考虑：

1）许多学者研究发现，在一种固体润滑剂中加入另外一种或多种固体润滑剂时会产生协同润滑效应，其润滑性能相比于使用单一固体润滑剂有很大提升[36—38]。固体润滑剂之间的协同润滑作用被认为是一种提高材料磨损抗力的有效途径[36—38]。有研究表明，当 MoS_2 与石墨同时使用时，石墨可以在边缘晶面形成氧的扩散屏障，并能在磨损表面把氧包裹起来，从而减轻 MoS_2 的氧化，达到提升其润滑性能的目的[39]。WS_2 的晶体结构和润滑机制与 MoS_2 相似，但 WS_2 的有效使用温度比 MoS_2 高大约 100 ℃，同时其润滑效果也好于 MoS_2（WS_2 摩擦系数为 0.03 ~ 0.05，MoS_2 摩擦系数为 0.05 ~ 0.1）[40—42]。然而到目前为止，几乎没有文献提到石墨和 WS_2 之间的协同润滑作用，特别是将它们作为固体润滑添加剂同时加入到金属基复合材料制成滑动电接触材料使用。笔者所在课题组采用热压法制备了四种不同成分的以石墨和 WS_2 为固体润滑添加剂的铜基自润滑复合材料，研究了成分对 Cu-石墨-WS_2 复合材料滑动电磨损性能的影响，发现在 Cu-石墨复合材料中添加适量的 WS_2 可以在电能损耗增加不多的同时，显著提高其磨损抗力[43]。

2）有报道指出，将两种或多种固体润滑组元合并使用是开发环境适应性材料的有效途径[44—46]。这种包含多种固体润滑组元的材料可以随外界环境的变化，通过其内部某一种或多种有效润滑剂向接触界面转移来维持较低的摩擦，从而在不同的环境中都能提供足够的润滑。石墨在大气或潮湿环境中具有优异的减摩特性，但在真空或干燥环境中却会丧失其润滑性能，因为石墨润滑特性的发挥需要磨损表面凝结的蒸气去中和其晶面边缘不饱和的悬键[47—48]。WS_2 具有和石墨相似的层状晶体结构，层与层之间的结合力较弱，易于滑移，因而被广泛用作固体润滑添加剂[40,49]。WS_2 可以在真空或干燥环境中提供较低的摩擦，但是在大气或潮湿环境中却表现糟糕，这是因为 WS_2 容易被氧或水蒸气氧化成 WO_3，导致其润滑性能下降[50—51]。笔者所在课题组以石墨为空气润滑剂，WS_2 为真空润滑剂，通过热压法将它们同时添加到铜基体中，以期各润滑组元在不同环境中能够发挥各自有效的润滑作用，从而提高复合材料的环境适应性[52]。

3）通过搭建电弧烧蚀装置，模拟放大研究滑动电磨损过程中摩擦接触界面出现的电火花烧损现象，以便对铜基自润滑复合材料的电弧烧蚀机理有一个更清楚的认识。目前已有学者对铜-碳复合材料的抗电弧烧蚀性能进行研究[53—54]。笔者所在课题组利用自制的电弧烧蚀装置对 Cu-石墨、Cu-WS_2 和 Cu-MoS_2 三种铜基自润滑复合材料的抗电弧烧蚀性能进行测试，并结合烧蚀形貌对复合材料的烧蚀过程和烧蚀机理进行分析，结果表明，铜基自润滑复合材料的电弧烧损机制主要有材料的氧化、熔化飞溅、内部化学反应以及疲劳脱落[29]。

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