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国际齿轮传动研究现状

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摘　要:介绍了国际上有影响的几个齿轮传动国际会议的情况。以最有影响力的德国国际齿轮传动会议为例,统计分析了近年来国际上齿轮传动的研究内容。讨论了齿轮传动设计、制造和应用中涉及的重点问题,包括提高承载能力、降低振动噪声、提高传动效率、节约制造资源、提高加工效率、避免环境污染等。对国际齿轮传动的主要研究进展和热点进行了综述分析。

关键词:国际齿轮会议;齿轮传动;研究现状

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Review of research on international gear transmissions

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Abstract: Several international conferences on gears is introduced, furthermore, the statistic analysis is conducted on the international gear research in recent years by taking example of the most influential Germany international gear conference. Some important issues on the design, manufacture, and application of gear transmissions is discussed including how to improve the load capacity, suppress vibration and noise, improve transmission efficiency, save resources, improve the efficiency of manufacture, and avoid the environmental contamination, and so on. Main progresses and research highlights of the international gear researches are also introduced and analyzed.

Key words: international conference on gears; gear transmission; research status

1　有影响的齿轮传动国际会议

国际会议,特别是有影响的高水平国际会议,由于其参加国家多、论文发表周期短、采用通用语言,是了解国际研究动态信息最有效的途径。研究者特别是发达国家的研究者均十分重视通过参加国际会议了解研究领域的国际学术动态。表 1 给出了笔者参加过的齿轮传动领域有影响力的国际学术会议,如德国国际齿轮会议、日本国际运动与动力传动会议、中国齿轮(机械传动、动力传动)国际会议;美国动力传动与齿轮会议。除此之外,英国、法国也不定期举行过或将举行国际齿轮传动学术会议,如 1994 年 9 月英国纽卡索国际齿轮会议、2014 年 8 月法国里昂国际齿轮会议等。在上述国际齿轮会议中,又以德国的国际齿轮会议影响最大,其特点是参加国家多、高水平学者多,学术界和工业界均很重视。笔者在对近年来举行的两次德国国际齿轮会议(2010 年和 2013 年)论文发表统计(见表 2)和阅读的基础上,介绍国际齿轮传动领域的研究现状。

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表 1 国际上有影响力的 4 个齿轮传动国际会议

国际会议名称	会议概况
德国国际齿轮会议	3～5 年举行一次。如 2005 年 9 月慕尼黑、2010 年 10 月慕尼黑、2013 年 10 月慕尼黑国际会议
日本国际运动与动力传动会议	10 年左右举行一次。如 1991 年 11 月广岛、2001 年福冈、2009 年仙台国际会议
中国国际齿轮(机械传动、动力传动)会议	通常 5 年举行一次。如 1988 年 10 月郑州、2001 年 4 月重庆、2006 年 9 月重庆、2011 年 10 月西安国际会议
美国动力传动与齿轮会议	通常 4 年举行一次。如 1996 年 10 月圣迭戈、2000 年 9 月巴尔迪摩(与 ASME 设计相关的 8 个领域合并举行)国际会议

表 2 齿轮的研究内容统计(2010 年和 2013 年德国国际齿轮会议) 篇

研究内容	圆柱齿轮	行星齿轮	锥齿轮	蜗杆	微小齿轮	面齿轮	非对称齿轮	小计
失效分析	26	2	1	1				30
齿形设计	16	2	4	2	1		7	32
动力学设计	10	7	3	1				21
摩擦学设计	15		1	2	1			19
传动方案	1	2			1	1		5
传动效率	9	5		2	1			17
振动噪声	19	3					1	23
齿轮加工	27		4				1	32
表面处理	17		1					18
齿轮材料	14							14
齿轮检测	4						1	5
故障诊断	7							7
总　计	165	21	14	8	4	1	10	223

2 国际齿轮传动研究现状

齿轮传动按其主要功能可分为:运动传递、动力传递、或运动和动力传递兼而有之。以运动传递为主要功能的齿轮传动,其研究目标是提高传动精度。而以动力传递为主要功能的齿轮传动,其研究则主要围绕以下几个方面进行:提高承载能力,降低振动噪声,提高传动效率,节约制造资源,提高加工效率,避免环境污染。2010 年和 2013 年在德国召开的两次国际齿轮会议论文中,绝大多数针对以动力传递为主要功能的齿轮传动,其研究所围绕的主要任务如图 1所示。笔者将结合文献分析,对齿轮传动提高承载能力、降低振动噪声、提高传动效率、节约制造资源、提高加工效率和避免环境污染方面的研究现状进行介绍。

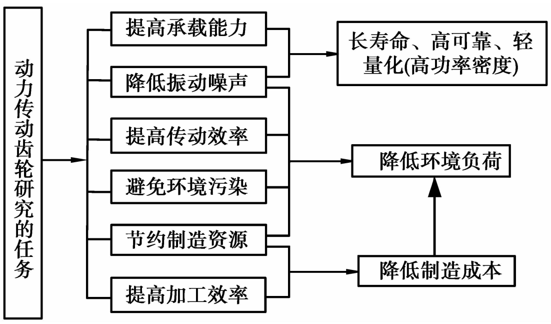

图 1 动力传动齿轮研究的任务

2.1 提高承载能力

对于传递动力为主的齿轮传动来说,承载能力是一个基本的性能要求,如何提高齿轮传动的承载能力已成为各国齿轮研究者的研究重点。要想提高齿轮传动的承载能力,必须对齿轮传动的失效机理有所了解,然后才能有针对性地提出提高齿轮传动承载能力的方法。齿轮传动的主要失效形式有轮齿折断、齿面点蚀、齿

面磨损、齿面胶合、塑性变形等。这些失效形式与齿根弯曲应力、齿面接触应力、齿面滑动速度与方向、轮齿动载荷、表面加工质量、材料热处理性能、润滑状态等因素相关。对于某种具体的失效形式，一部分因素起主要作用，而另外一部分起次要作用。因此需要针对不同失效形式采用不同的设计制造方法来控制其主要影响因素以提高承载能力。目前主要通过齿形设计来降低齿根弯曲应力、齿面接触应力和减少齿面滑动，通过动力学设计来降低动载荷，通过润滑设计改善齿面润滑状态，通过选用合适的冷热加工制造方法来提高表面加工质量和热处理后的性能。下面结合德国国际齿轮会议文献分析分别对齿轮传动的齿形设计、动力学设计、润滑设计和齿面加工处理方面的最新研究动态进行综述。提高齿轮传动承载能力的途径如图 2 所示。

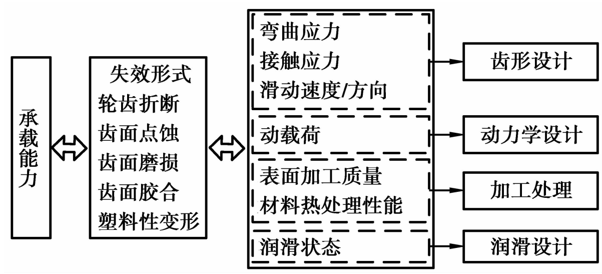

图 2　提高齿轮传动承载能力的途径

2.1.1　齿形设计

为了提高齿轮传动的承载能力，国际齿轮研究者在现有齿轮齿形基础上进行了不少创新或改进。渐开线锥齿轮能使相交轴传动实现线接触，具有强度大、刚性好、传动平稳等特点，因此受到齿轮研究者的重视。Fuentes 等[1]以提高承载接触性能和减振降噪为目的，对渐开线锥齿轮的齿面修形方法进行了研究，并提出了新的修形方法，使齿面接触应力比传统齿形接触应力的下降幅度超过了 50%。Traut 等[2]也对渐开线锥齿轮齿面修形方法进行了研究，并通过加工仿真验证了该方法可在间断工作的插齿机或磨齿机上使用。Traut 等[3]研究了制造偏差对渐开线锥齿轮承载接触性能的影响，指出与圆柱齿轮相比，渐开线锥齿轮对制造误差和齿面修形更为敏感。Tsai 等[4]对螺旋锥齿轮进行了研究，提出了一种具有近似线接触的高承载螺旋锥齿轮，该螺旋锥齿轮具有比传统锥齿轮承载能力大且对制造误差不敏感的特点。作为适用于单向传动的齿轮，非对称齿形越来越受到人们的关注。非对称渐开线齿形具有如下优点[5-9]：1）提高了轮齿的弯曲强度和接触强度；2）减小了切向接触力，有利于减少齿面的微点蚀；3）具有良好的动态性能；4）对中心距误差不敏感；5）加工简单，可采用与普通渐开线齿轮相同的滚、剃和磨削加工。Kruger[5]等讨论了非对称渐开线齿形的承载能力设计计算的基础问题，提出了一种可以考虑塑性变形的非对称渐开线齿形的承载能力计算方法。Dorofeev 等[6]对非对称渐开线齿形进行了优化和应力计算。Bercher 等[7]对非对称渐开线齿轮的动力学特性进行了仿真和实验研究，指出采用非对称齿形可以平衡降噪和提高承载能力两者之间的矛盾。Masuyama 等[8]对非对称渐开线齿轮强度进行了仿真分析。Alipiev[9]对少齿数的非对称渐开线齿轮进行了研究。Seidler 等[10]对非对称齿形的锥齿轮进行了研究，并指出非对称齿形的锥齿轮可能广泛应用于对反向传动要求不高的场合。

2.1.2　动力学设计

在齿轮承载能力的研究中，动力学设计主要关注动载荷。Schlecht 等[11]基于动力学，在弹性范围内对轮齿应力进行了分析。Qin 等[12]对风电齿轮箱变工况下的动力学与轮齿动载荷抑制进行了研究。Bai 等[13]对不同工况下的齿轮动态啮合力进行了计算和分析。Schlecht 等[14]在考虑齿轮传动系统动态特性的情况下对齿轮进行了应力分析。Weber 等[15]对渐开线齿轮的动态齿面载荷和局部应变历程进行了仿真。Beermann 等[16]对齿轮箱的动态和静态载荷进行了联合仿真。Baumann[17]等在行星齿轮动力学分析的基础上，对行星齿轮均载系数和承载能力进行了计算。Papies 等[18]对电梯齿轮箱进行多体动力学仿真以获得齿轮载荷谱，然后对齿轮寿命进行预测。Hu 等[19]考虑齿轮传动系统动力学特性，根据混合弹流润滑理论建立了基于应力的渐开线齿轮疲劳计算模型，并预测了渐开线齿轮的点蚀疲劳寿命，指出表面粗糙度对临界应力分布和疲劳寿命均有显著的影响。基于动力学的功率分流传动均载设计也越来越受到研究者的关注[20-21]。Liu 等[20]建立复合行星齿轮的平移-扭转动力学模型来研究制造误差对动态均载的影响，指出不同零部件的制造误差对动态均载行为的影响是完全不同的。Wang 等[21]建立了 4 条路径能量分流的齿轮传动系统简化动力学模型来研究安装误差对均载的影响，指出低速级的安装误差对均载的影响比高速更大，因此必须研究控制低速级齿轮的安装误差。

2.1.3 加工处理

为了提高齿轮齿面的承载能力,通常会对齿轮表面进行处理,比如齿面涂层、改变齿轮齿面的织构、喷丸、渗碳/氮等。这些处理可改善齿面的啮合条件,减少齿面失效的发生,对提高齿轮传动的承载能力有重要作用。Stahl 等[22]通过在双圆盘试验机和 FZG 效率试验机上测量摩擦系数和传动效率,研究了表面织构和涂层对摩擦系数和传动效率的影响。Fujii 等[23]研究了碳化钨/碳涂层对表面摩擦、磨损和表面耐久性的影响,指出 WC/C 涂层可以提高齿轮寿命,但当发生涂层剥落之后,其寿命与无涂层齿轮相当或者更低。Krzan 等[24]对碳化钨涂层在减少浸油深度条件下的擦伤性能进行了研究,指出碳化钨涂层可明显减少齿轮的擦伤,从而提高承载能力,且涂层齿轮的磨损微粒比没有涂层的齿轮小。Miyachika 等[25]研究了齿面渗碳和轮齿端面渗碳对轮齿残余应力和弯曲强度的影响。Morikawa 等[26]研究了细粒喷丸强化对真空碳氮共渗齿轮齿面耐久性的影响,指出真空碳氮共渗可以提高齿面承载能力,但真空碳氮共渗后的喷丸会降低其承载能力,喷丸之后的抛光可以弥补喷丸的缺点并使齿面强度提高。Hohn 等[27]研究了齿面磨削烧伤对齿轮承载能力的影响。Klocke 等[28]研究了硬齿面精加工引起的残余应力对齿轮寿命的影响。

2.1.4 润滑设计

齿轮传动润滑设计的优劣也会影响到齿轮传动的承载能力,随着人们环境保护意识的增强,齿轮研究者在进行齿轮传动润滑设计时也考虑了润滑设计对环境的影响。Brecher 等[29]介绍了环境友好型齿轮润滑系统的概念和设计思路,通过可降解生物润滑剂在重载齿轮传动润滑过程中的化学转移涂覆,形成高性能齿面润滑膜,从而实现对环境友好的润滑系统。Ohshima 等[30]对齿轮啮入啮出区域润滑油流动特性对润滑性能的影响进行了实验研究。Li 等[31]对润滑接触区的微点蚀与润滑条件的关系进行了理论与实验研究。Kubo 等[32]应用接触弯曲疲劳试验机对混合润滑条件下因摩擦引起齿面次表面裂纹扩张所导致的齿面接触弯曲疲劳进行了实验研究。Snidle 等[33]对接触齿面混合润滑和齿面接触疲劳的预测机理进行了研究。Jamali 等[34]研究了齿面修形对齿面弹流动力润滑的影响,指出齿顶修形会产生高的接触应力并使润滑油膜变薄。Horl 等[35]对具有织构滑动面的低摩擦密封件进行了实验研究,提出了一种可明显降低传动系统密封损失的表面织构。

2.2 高效传动与节能降耗

对用于传递动力的齿轮传动,效率是一个很重要的性能指标。低的传动效率不仅会造成传递功率的损失,而且由于损失的功率大多转换为热能,使传动系统的温度升高,容易造成润滑失效,从而降低传动系统的使用寿命。齿轮传动的效率与具体的传动形式直接相关,可通过采用高效率的齿轮传动形式来直接提高传动效率。齿轮传动效率的损失按其主要影响因素可分为:动力传动损失和非动力传动损失。动力传动损失主要为齿面摩擦损失,而非动力传动损失主要包括风阻损失、搅油损失和密封损失。目前齿轮传动的效率研究主要集中在新型传动形式、动力传动损失和非动力传动损失这 3 个方面,如图 3 所示。Hohn 等[36]采用具有低效率损失的行星齿轮机构减少齿轮副的摩擦损失,使 NGWN 行星齿轮机构在实现高效率的条件下满足了大传动比的要求。Stahl 等[37]研究了脂润滑条件下平行轴齿轮的传动效率,指出在大浸油深度和高转速情况下,与油润滑相比,脂润滑可以明显减小空载损失。Stahl 等[38]研究了脂润滑条件下蜗杆的传动效率,与油润滑相比,在低转速下脂润滑效率较高。Handschuh 等[39]和 Concli 等[40]考虑润滑油黏度和空气密度的影响,采用流体动力学分析和流场实验方法对高速齿轮风阻损失、搅油损失和旋转油封损失进行定量研究。Handschuh 等[39]对高速齿轮传动系统的非动力传动损失进行了实验研究。Concli 等[40]研究了直齿轮的轮齿几何结构对风阻损失的影响。

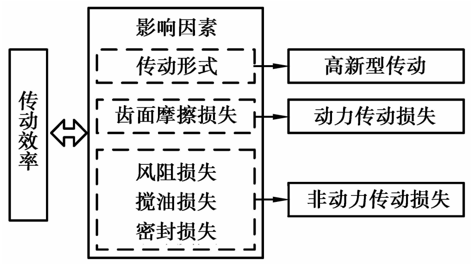

图 3 传动效率的影响因素

2.3 振动与噪声控制

齿轮传动振动与噪声的控制其目的主要是改善传动系统的动态性能和操作者的工作环境,这与承载能力设计中的动力学设计的目的是不同的,动力学设计主要是为了降低传动系统的动载荷以提高传动系统的承载能力。

2.3.1　齿轮振动控制

齿轮传动振动控制的研究文献主要有多级功率分流传动的振动建模与控制、多工况变载荷下的振动分析与控制,以及摩擦对振动特性的影响等。Lan 等[41]建立了多级分流齿轮传动系统动力学模型,获得了振动加速度的时程曲线和噪声频谱,分析了齿轮参数对动态响应和结构噪声的影响,并通过调整齿轮设计参数将齿轮箱噪声降到约 10 dB。Xiang 等[42]研究了两级行星齿轮系统的扭转和平移固有振动特性,以及固有特性对质量、转动惯量、啮合刚度、轴承刚度以及耦合刚度的灵敏度。Heider 等[43]研究了行星齿轮传动系统的振动激励行为及其影响因素。Giacometti 等[44]通过有针对性的测量和仿真,实现多工况变载荷下车辆动力传动系统的振动控制。Magyar 等[45]建立了蜗杆传动的摩檫学和动力学模型,分析了摩擦对蜗杆传动振动特性的影响。

2.3.2　噪声控制

齿轮传动噪声控制的研究文献主要有用统计能量法预测振动和噪声、齿轮噪声的声学心理学评价、齿轮噪声引起心情烦躁的客观评价、基于加载接触分析的齿轮噪声控制以及汽车齿轮敲击噪声建模分析和实验等。根据统计能量分析基本原理,Liyan 等[46]提出了统计能量分析模型,用于预测齿轮箱的噪声。为了预测用户对齿轮噪声的反应,Brecher 等[47-48]提出采用心理声学评价法来评价齿轮箱的噪声,并通过实验分析和数值仿真验证了该方法的有效性。Lutz[49]提出采用合成的心理声学量值来客观描述齿轮箱噪声引起的用户的不安情绪,以实现齿轮箱噪声的分析和评价。Borner 等[50]提出基于加载接触分析的噪声激励计算模型,从而实现了传动装置的低噪声设计。Albers 等[51]建立了基于齿轮敲击仿真的噪声分析模型,用以评估汽车齿轮箱的敲击噪声水平和噪声源。Kadmiri 等[52]对汽车齿轮箱的敲击噪声进行了理论和实验研究,指出敲击噪声与系统的冲击恢复系数、激励幅值和阻力矩密切相关。

2.4　齿轮绿色制造

随着全球资源短缺和环境污染的加剧,高效、节能、低污染的齿轮绿色制造方法越来越受到人们的关注。为了提高制造效率和性能并节约资源,研究者们对前向挤压和横向挤压轧制齿轮的金属流向、残余应力和齿轮强度,少齿数大螺旋角斜齿轮的成形辊轧,基于高生产率和低烧伤的磨削量优化等进行了研究。Tachikawa 等[53]研究了少齿数大螺旋角斜齿轮成形辊轧的成形偏差产生机理,发现冲模的挤压率会影响齿廓偏差。Schoo 等[54]采用 Barkhausen 噪声法分析了齿轮齿廓成形磨削的过程优化及过程控制。Heuer 等[55]通过优化切削量的分配来提高齿面磨削的生产率。Hohn 等[56]对齿面磨削烧伤对热处理齿轮齿面承载能力的影响规律进行了研究。

为了减小或避免环境污染,研究者们对干式切削或最少切削液滚齿、TiSiN 涂层滚刀的干式切削效果、齿轮材料硬度对干式滚齿切削的影响、无矿物油冷却液齿轮加工、特种切削油等进行了研究。Shutou 等[57]对比了最少切削液滚齿和干式滚齿的切削性能。Kurokawa[58]等对钛族陶瓷涂层(如 TiN、TiCN、TiSiN 和 TiAlN 等)高速钢滚刀的耐磨度以及涂层氧化对月牙洼磨损的影响进行了实验研究。Dwuletzki 等[59]提出了一种无矿物油的新冷却液,通过采用新的黏性水基润滑剂实现齿轮加工的冷却与润滑。Baly 等[60]通过特种切削油的实验研究,指出切削油的硫含量、活性及浸润性对切削油性能有重要影响。

2.5　齿轮材料

随着齿轮材料研究的不断深入,根据齿轮传动的不同用途,齿轮材料不再局限于普通的锻造钢材,金属烧结材料、不同配对的金属和塑料材料,高分子聚合物材料也广泛应用于齿轮传动。齿轮研究者针对采用金属烧结材料、塑料材料和高分子聚合物材料的齿轮的性能进行了大量研究。Fiodin 等[61]和 Dizdar[62]比较了金属烧结和锻造齿轮的性能,指出与锻造齿轮相比,金属烧结齿轮具有耗材少、加工去除材料少和成本低的优点,但金属烧结齿轮的性能不及锻造齿轮。提高烧结齿轮性能的关键在于使齿轮表面硬化层深度更深并得到高密度的齿轮芯体。Letzelter 等[63]建立了塑料齿轮的齿间载荷分配模型,该模型可以获得不同温度、湿度和转速下的传动误差、啮合刚度、啮合力、齿间载荷分配状况和齿根应力。Predki 等[64]对钢/塑料配对的交错轴斜齿轮的承载能力进行了研究,提出了一种新的承载能力的预测方法。Wood 等[65]对比了钢-钢、钢-塑料和塑料-塑料齿轮对的传动性能,发现钢-塑料齿轮对的扭矩和传动误差波动明显而塑料-塑料齿轮对可以改善这一状况。对于同一种塑料,塑料-塑料齿轮对要优于钢-塑料齿轮对。Small 等[66]研究了 Peek 聚合物(一种高性能热塑性聚合物)齿轮的性能范围,指出采用这种齿轮代替金属齿轮可以提高传动效率、降

低噪声并大大减小惯性质量。Nakamura 等[67]在氩和甲烷混合气体环境中,采用不平衡磁控溅射方法在聚乙醛齿轮(一种在日本广泛采用的塑料齿轮)表面形成一层黏附性能良好的类金刚石碳涂层,通过实验研究发现,这种表面有类金刚石碳涂层的聚乙醛齿轮的耐久性能得到了很大的改善。

2.6 齿轮测量与故障诊断

齿轮的制造误差不仅影响动力传递的平稳性,导致传动系统的振动噪声和动载荷,而且影响齿轮齿面的接触性能,从而影响齿轮传动的承载能力和使用寿命。基于齿轮传动系统动态性能测试的故障诊断是预测齿轮失效的重要手段,越来越受到研究者们的重视。Hartig 等[68]比较了三坐标测量机、激光跟踪仪和关节杆测量机在大型齿轮测量上的应用效果,指出三坐标测量机的测量结果具有很好的重复性,而激光跟踪仪和关节杆测量机与操作者有很大的关系,并给出了使用这 3 种测量仪器进行大型齿轮误差测量的一些建议。Rohr[69]提出了在高精度三坐标测量机上检测 Curvic 联轴器的虚拟测量方法,以代替 Curvic 联轴器的专用检测工具。Kapelevich 等[70]对非对称渐开线齿轮进行了精度检测。Pahlke 等[71]发展了一种可对齿轮进行快速定位和测量的在线测量技术。Kurokawa 等[72]研究了齿轮偏心误差所引起的边频振动特征。Clerc 等[73]将齿轮-电机耦合模型应用于齿面失效的测量评估中,通过电流等电测量的监测对传动系统进行故障诊断。Andrei 等[74]基于动态过载的测量对齿轮传动的失效进行了预测。Geramitcioski 等[75]提出了采用激光传感器对齿轮进行齿面损伤诊断的方法。Tanaka 等[76]基于振动信号对齿轮齿面的失效进行了检测诊断。Vizintin[77]提出了齿轮传动智能诊断系统的概念,并对其实现方案进行了阐述和分析。

3 结 语

1)根据 2010 年和 2013 年德国齿轮国际会议论文的统计结果,齿轮系统动力学与振动噪声分析(44 篇)、齿轮加工(32 篇)、齿形设计(32 篇)、失效分析(30 篇)、摩擦学设计(19 篇)、表面处理(18 篇)、传动效率(17 篇)、齿轮材料(14 篇)仍然是齿轮传动研究的关注点。

2)以提高加工效率、节约资源、保护环境为目的的齿轮设计制造得到了越来越多的关注。

3)提高齿轮传动的综合性能,需要通过设计、制造和材料热处理等多项技术的综合应用。

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