第八届"全国激光加工学术会议"
节目手册

2006年 11月25-26日
广州

Advanced Program on 6th China National Conference on Laser Material Processing- CNCLMP? 006

November 25-26, 2006

Guangzhou, China

中国光学学会激光加工专业委员会 编制

Laser Processing Committee of China Optical Society ,LPC-COS

22

第八届“全国激光加工学术会议”
节目手册

2006 年 11 月 25-26 日
广州

Advanced Program on 8th China National Conference on Laser Material Processing- CNCLMP? 006

November 25-26, 2006

Guangzhou, China

中国光学学会激光加工专业委员会 编制
Laser Processing Committee of China Optical Society ,LPC-COS

第八届全国激光加工学术会议日程安排

Program for 8th China National Conference on Laser Materials Processing-CNC-LMP'06

时间		会议内容		
25日上午		**开幕式（地点：主会场）**		
	8:30-9:00	1．中国光学学会激光加工专业委员会主任 邓树森研究员 致欢迎词		
		2．科技部孙中发处长讲话		
		3．广州市科协领导讲话		
		4．华南师范大学领导讲话		
		特邀报告（地点：主会场）主持人：邓树森研究员，刘文今教授		
	9:00-9:30	The Growth of Laser Material Processing as a Science and an Industrial Process 英国利物浦大学 William Steen 教授，翻译：文效忠教授，香港理工大学		
	9:30-10:00	Welding with Strongly Focusable Laser up to 6kW 德国斯图加特大学 Friedrich Dausinger 教授，翻译：陈继民教授，北京工业大学		
	10:00-10:30	Progress in Laser Direct Manufacturing by Laser Metal Deposition and Selective Laser Melting 法国 CEA/GERAILP Pascal Aubry 博士，翻译：钟敏霖教授，清华大学		
	10:30-11:00	Laser Micro- and Nanoprocessing using short laser pulses 德国汉诺威激光中心主任 Andreas Ostandorf 博士，翻译:曾晓雁教授,华中科技大学		
	11:00-11:30	Laser Material Processing and Characterization at Micro/Nano-scales 美国 Nebraska-Lincoln 大学 Lu Yongfeng 教授		
	11:30-12:00	Laser Cladding -Application in Germany 德国 BIAS Harad Kohn 博士，翻译：彭智学博士，GE		
25日下午		**第1分会场：激光强化与材料制备** **主持人：王茂才研究员，张庆茂教授**	**第2分会场：激光直接制造** **主持人：钟敏霖教授，黄卫东教授**	**第3分会场：激光微纳加工** **主持人：左铁钏教授，李正佳教授**
	1:40-2:00	Direct Manufacturing of Porous Coating of NiTi alloy by Laser Spraying Process, YQ.YANG,香港理工	（邀请报告）高性能复杂结构金属零件的激光快速成形,黄卫东,西北工大	飞秒激光制备微纳米阵列孔金属膜的试验研究,杨洗陈,天津工大
	2:00-2:20	激光熔覆制备钛基耐热—耐磨功能梯度材料,赵金，海军航空工程学院	采用区域选择激光熔化技术制造铝合金零件的研究,张冬云,北京工大	PMMA 基 PCR 生物芯片及其准分子激光制备技术的几个关键问题,陈涛,北京工大
	2:20-2:40	钛合金基体上激光熔覆制备钛铝化物基复合涂层组织特征的研究,李晓莉,清华大学	选区激光熔化快速成型制造精密金属零件技术,吴伟辉,华南理工	薄膜包覆法连接一维双壁碳纳米管宏观体接头的激光强化研究,龚涛,清华大学
	2:40-3:00	铝合金表面 MoSi2SiC 复合涂层的激光熔覆制备,杨森,内蒙古工大	Nd:YAG 激光熔覆快速制造技术研究,卢尧君,华中科技大学	单脉冲飞秒激光作用下晶态 Ge1Sb2Te4 相变薄膜的非晶化过程,黄素梅,华东师范大学
	3:00-3:20	ZL102 合金表面激光熔覆 Al-Si+Al2O3 复合涂层,孙荣禄,天津工大	Ti-6Al-4V 合金的激光净成形制造及其显微组织,刘勇,通用电气公司	激光烧蚀法制备氧化锌纳米颗粒及其光谱特性研究,赵艳,北京工大
	3:20-3:40	钛合金激光熔覆（Ti+ AlNi）（Cr2O3+CeO2），崔爱永,海军航空工程学院	激光沉积制备 A15-Nb3AlB2 叠层金属间化合物复合材料的工艺、组织与性能,何金江,清华大学	紫外激光辐照对碳纳米管形态的影响,张勇,清华大学
	3:40-4:00	强碳化物形成元素在激光制备原位合成颗粒增强铁基复合涂层中的作用,马明星,清华大学	激光净成形制造金属零件过程稳定性研究,李延民,通用电气公司	掺铒对激光烧蚀制备纳米硅晶薄膜形貌的影响,周阳,河北大学
	4:00-4:20	NiTi 合金激光气体氮化对其生物活性的影响,张松，沈阳工大	激光多层沉积修复定向凝固镍基高温合金叶片,朱晓峰,清华大学	硅基板激光微熔覆电子浆料制备导体研究,王小宝,华中科技大学
	4:20-4:40	Cu-Zr-Al 非晶合金成分设计与激光熔覆,王存山、大连理工	激光快速成形过程中熔池形态的演化,陈静，西北工大	心血管支架激光切割工艺研究,蒙红云,华南师大
	4:40-5:00	激光合金化对疲劳裂纹扩展速率的影响,李正阳,清华大学	Ti-Ni 合金选区激光熔化快速成型基础实验研究,王池林,华南理工	激光微细熔覆快速制造厚膜热敏传感器的技术研究,王少飞,华中科技大学

	5:00-5:20	（MoO3+B2O3）对镍基合金激光熔覆层的影响,王文丽,郑州大学	激光快速成形过程的热行为及其影响,谭华,西北工大	MEMS 芯片激光封装技术的研究,陈一梅,厦门大学
	5:20-5:40	生物医用钛合金的激光表面改性,张春华,沈阳工大	激光直接烧结成形金属零件的实验研究,郭华锋,江苏大学	激光微细熔覆快速制备空芯薄膜电感的研究,代青龙,华中科技大学
	5:40-6:00	球墨铸铁表面激光点状合金化组织及热疲劳性能研究,王海龙,清华大学	一种新的用于选区激光熔化快速成型扫描路径的生成算法,许丽敏,华南理工大学	大功率半导体激光器材料加工技术最新进展,苏国强,北京工业大学
	6:00-6:20	塑料模具激光精密修复技术的研究,常明,华南师大	激光直接制造和再制造中的三维模型直接分层技术,靳晓曙,天津工大	激光辅助多层纳米级薄膜沉积及表面微结构制备,邵天敏,清华大学
	7:00-9:00	**晚宴**		
26日上午		**第 1 分会场：激光焊接** **主持人：陈彦宾教授，吴让大总经理**	**第 2 分会场：激光器与激光加工系统** **主持人：张国顺教授，吴建国总经理**	**第 3 分会场：激光冲击与强化** **主持人：杨洗陈教授，张永康教授**
	8:00-8:20	高功率焊接船板的试验研究,杨洗陈,天津工大	大功率 300W 固体激光器的研究,陈义红,广州安特公司	基于激光冲击波的三维无损防伪标识的基础研究,张永康,江苏大学
	8:20-8:40	船用钢板大功率激光深熔焊等离子体研究,李国华,上海交大	一种用于激光烧结陶瓷的大功率 CO_2 激光,黄雅峥,北京工大	激光冲击处理钛合金的研究,邹世坤,625 所
	8:40-9:00	1420 铝锂合金 YAG 激光焊接,肖荣诗,北京工大	高功率双包层光纤激光器温度分布的有限元分析,陈子伦,国防科技大学	受控激光喷丸强化技术,孙月庆,江苏大学
	9:00-9:20	激光拼焊门内板冲压有限元仿真及实验研究,阎启,宝钢	新型激光高速 PCB 打孔系统的研究,王萌,天津大学	冲击工艺对铝合金激光熔覆的影响,孙福娟,海军航空工程学院
	9:20-9:40	CO_2 激光填丝焊工艺及机理研究,姚远,一汽	激光毛化加工新型调制斩光系统的设计,万大平,上海交大	球铁曲轴零件激光冲击强化的研究,杨建风,江苏大学
	9:40-10:00	CO_2 激光-MIG 复合对接焊熔透工艺研究,双元卿,清华大学	基于 JPEG 格式的激光图像扫描技术研究,童博,华中科技大学	45CrNi 钢激光淬火与中频感应淬火摩擦磨损对比试验的研究,石岩,长春理工大学
	10:00-10:20	CO_2 激光-MIG 复合焊接熔滴过渡力学行为,雷正龙，哈工大	基于 ObjectARX 的激光切割数控自动编程系统,沈显峰,工程物理研究院	曲轴激光淬火加工工艺研究,王云山,天津工大
	10:20-10:40	铝合金激光双光点焊接,姚伟,625 所	激光再制造超细粉送粉器的试验研究,冯立伟,天津工大	工艺参数对 YAG 脉冲激光熔覆层微观形貌的影响,姜伟,海军航空工程学院
	10:40-11:00	热源空间位置对激光一电弧复合焊接焊缝成形的影响,高明,华中科技大学	激光再制造三维运动光束头,张兴泉,天津工大	工艺参数对同轴送粉激光熔覆层质量的影响,季霞,江苏大学
	11:00-11:20	激光焊接高强度镀锌钢热循环的研究,伍强,湖南大学	激光加工温度场 CCD 检测中的温度标定研究,陈娟,天津工大	激光喷丸成形中残余应力的研究,曹向广,江苏大学
	11:20-11:40	激光-MIG 复合焊视觉传感系统及熔池背面图像的检测,王康健,清华大学	激光熔池动态过程检测研究,雷剑波,天津工大	板料激光喷丸强化与机械喷丸强化应力场的数值研究,杜建均,江苏大学
	11:40-12:00	AA6063-T6 铝合金激光焊接实验研究,吴世凯,北京工大	激光切割排样系统在硅钢板材加工中的应用,宋连超,哈尔滨理工大学	
		第 1 分会场：激光焊接与切割 **主持人：张拯研究员，杨永强教授**	**第 2 分会场：激光烧结与沉积** **主持人：蒋毅坚教授，王健研究员**	**第 3 分会场：激光新应用、过程模拟** **主持人：，朱晓教授，郭少陵研究员**

26日下午	1:40-2:00	钛合金激光填丝焊接,陈新松, 625所	功能陶瓷激光烧结技术的研究,季凌飞,北京工大	双脉冲固体激光技术在金属加工应用中的特点,蔡静军,环球科技
	2:00-2:20	激光深熔焊小孔型气孔的产生及其防治技术的研究,张晓红,清华大学	激光烧结合成 ZrW2O8 研究,吴天安,郑州大学	用激光热应力法评估薄膜蠕变性能的理论研究及有限元模拟,李粤,华南农业大学
	2:20-2:40	双金属带锯条异种接头的 CO_2 激光焊接实验研究,祁俊峰,北京工大	激光烧结陶瓷温度场的数值模拟,杜新宇,北京工大	激光清洗技术应用初探,刘建华,航空精密机械研究所
	2:40-3:00	铝-钛异种合金的激光熔钎焊,封小松,哈工大	$Al_2(WO4)_3$ 的激光烧结合成及特性研究,王少辉,郑州大学	基于 ABAQUS 的激光冲击波诱导残余应力场的有限元模拟,倪敏雄,江苏大学
	3:00-3:20	黄铜-低碳钢异种金属激光深熔钎焊实验研究,皮友东,北京工大	激光烧结锆钛酸钡压电陶瓷,付宗义,北京工大	激光划痕法测定薄膜界面结合强度的数值模拟,唐翠屏,江苏大学
	3:20-3:40	脉冲激光点焊铝合金工艺特性研究,陶汪,哈工大	激光烧结快速合成 La2(MoO4)3 材料,王征,郑州大学	激光熔覆成形薄壁金属制件精度的预测模型,徐大鹏,江苏大学
	3:40-4:00	激光切割火花簇射行为的实验研究,张永强,清华大学	激光引燃自蔓延合成 Al-Ti-C 中间合金 DSC 分析,潘学明,大连理工	粉末流场的数字图像处理技术,杨楠, 天津工大
	4:00-4:20	CO_2 激光气化切割非金属材料的机理分析,谢小柱,湖南大学	激光辐照对 La0.67Ca0.33MnO3 薄膜结构和电输运特性的影响,常雷,北京工大	激光技术在金属板料成形中的研究进展及其应用,陈毅彬,江苏大学
	4:20-5:00	脉冲激光修锐青铜金刚石砂轮烧蚀机理研究,朱定军,湖南大学	激光辐照诱导 PVDF 导电性的研究,姬亚玲,北京工业大学	选择性激光烧结的温度场研究进展,蒋文波,南昌航空工业学院
	5:00-5:20	脉冲激光铣削的机理研究与应用,袁根福,安徽建筑工业学院	脉冲激光溅射沉积制备 La0.67Ba0.33MnO3 薄膜,常雷,北京工大	光纤连接损耗的研究,杨小丽,西安理工大学
	5:30-6:30	激光新技术新产品报告会（地点：主会场） 主持人：刘永桢研究员，宋威廉研究员		
	6:30-7:10	公布优秀学生论文评选结果、发奖；闭幕式（地点：主会场） 主持人：刘文今教授		
	8:00-10:00	珠江夜游		

会议作息时间：

早　　餐：　7:00- 8:00
上午会议：　8:30-12:00
午　　餐：　12:00-13:00
下午会议：　13:40-18:20
晚　　餐：　18:20-19:00

会议地点：

主会场：
第 1 分会场：
第 2 分会场：
第 3 分会场：

此为试读，需要完整PDF请访问：www.ertongbook.com

GROWTH OF LASER MATERIAL PROCESSING AS A SCIENCE AND AN INDUSTRIAL PROCESS

Paper #

William M Steen

Em.Professor Liverpool University and Distinguished Research Fellow Cambridge University, UK.

Abstract

With the invention of the laser in 1960 came the realisation that we now had a new form of industrial energy: optical energy in large and controllable quantities. This is one of the most versatile forms of energy available to us and should lead to numerous technical breakthroughs, just as happened with the invention of the dynamo generating electricity in 1831. Numerous developments have indeed taken place but all have been held back somewhat by the cost and size of the laser equipment. This blockage is about to change with the introduction of high brightness, compact and robust fibre, disc and diode lasers.

This paper reviews these developments in equipment and processes and considers how this might impact on China and laser processing in general. The purpose of the paper is to act as an index to the current state of activity in this subject. It shows two things in particular: Firstly that lasers are being introduced into industry at such a rate that it is now imperative that engineering colleges and universities teach laser processing within their syllabi as a major engineering subject; for that is what the subject of laser material processing has become; and secondly, that manufacturing strategy is being fundamentally challenged by the opportunities opened by the laser.

Introduction

The laser is today as fundamental an invention as the dynamo was in the 19th century. It has introduced a new form of industrial energy, optical energy, and made it available in large and controllable quantities. But the early machines were large, tended to be unreliable and were very expensive. Thus around the world only a few well funded laboratories grew up. From these laboratories came an impressive flow of patents and new processing techniques, but only the wealthiest manufacturing concerns became involved. From the 1990s the concept of laser cutting was fully accepted by industry as cost effective and of a high quality. In order to fully utilise the expensive equipment many small businesses formed as job shops taking in cutting work, usually with a very swift turn around time. Competition was strong and so profitability was low. This could well have remained the state of affairs for many years, in which case the laser would have been seen historically as an exotic form of manufacturing, something everyone talked about but few actually used.

Today this is about to change with the introduction of compact, robust and efficient high brightness lasers in the form of fibre, disc and high power diode lasers. This paper will summarise some of the main changes that have occurred in the last ten years or so and predicts that the availability of cheap optical energy will revolutionise small businesses; making laser technology peculiarly suitable for the Chinese cottage industries.

The main changes considered are developments in: high power sources, laser cutting, welding, additive manufacture, marking and engraving, micro-processing and surface engineering.

The commercial growth in most of these areas is of the order of 10-20%/year. It would be reckless for this growth to be directed by enthusiastic amateurs. This engineering subject needs properly trained engineers in order to grow efficiently and consistently. Engineers should have a deep understanding of the nature of the energy being applied. Optical energy has many more characteristics than as a source of power. The subject of optical engineering needs to be taught in engineering schools and universities.

Developments in high power laser sources

Three new laser sources that are compact, enduring and robust have been developed in the last decade or so. They are: high powered diode lasers, disc lasers and the fibre lasers. Of these the fibre laser is the outstanding one. The fibre laser has no moving or adjustable parts; they are all in fixed alignment. They have a wall plug efficiency of 25-30% compared to the CO_2 laser of 12% or the Nd:YAG of 5-8%. The beam is delivered directly from the fibre in which it is generated. These fibres can be very fine, of the order of 100μm, and perform almost as mono-mode wave guides. Thus low order beams can be produced with near Gaussian profiles at the short infra red wavelength of 1.03-1.07μm for a Yb (ytterbium) doped fibre or 1.54μm for an Er (Erbium) doped fibre (which is an "eye-safe" wavelength). This means the focal spot can be as little as 10μm due to the shorter wavelength compared to the CO_2 laser where 100μm is considered very good. This is an increase in power density of 100 times. This high brightness, although something longed for over many years, has its disadvantages in that the high electromagnetic field at the focus can cause air breakdown with consequent plasma blocking.

Single mode CW power from these lasers has risen dramatically in the last few years to 2-5kW/ fibre or 50kW for bundles of fibres, as currently offered by IPG and shown in Fig.1.

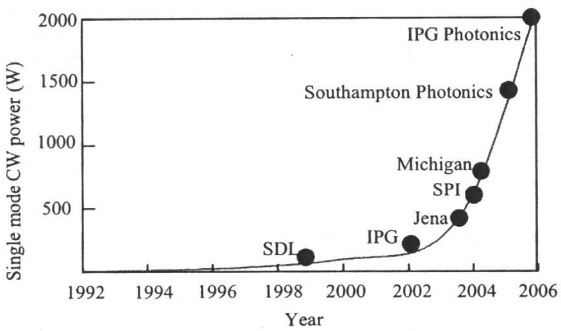

Fig. 1 Growth in power for ytterbium doped fibre lasers at 1.03-1.07μm

These lasers grew from the collapse of the telecom bubble that left many R&D organisations seeking new outlets for their know-how, which included fibre laser amplifiers and from the demise of the Soviet Union that freed Professor Gapontsev, who worked at IRE Moscow and is now the President of IPG, allowing him to develop Russian know-how in the West. This form of laser depends on reliable high powered diode lasers, reliable coupling between fibre and diode and high quality fibres; all of which are now available.

If the beam quality can be relaxed, as is required for most surfacing and some welding applications the direct use of diode sources becomes possible. A diode has a wall plug efficiency of around 40-45% with a possible lifetime expectancy of around 10 years. IPG believe they can couple these diodes into a 600-800μm fibre. Diodes can be produced with high powers at various wavelengths. At present the search is on to find a blue source for high power lighting applications via GaN diodes; such research is bound to impact on the material processing.

These new sources are truly exciting since the intrinsic cost of a fibre or diode laser is not particularly high, Fig 2. The view into the not so distant future is for cheap and reliable optical power. So how will this be used?

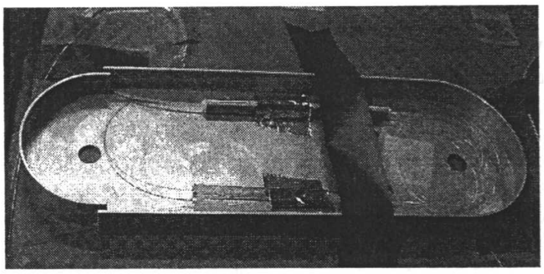

Fig. 2 The resonator chamber of a fibre laser, showing the coupling to the diode input and the amplifying fibre.

Developments in Cutting [3]

Laser cutting is noted for the speed and quality of the process as well as the ability to cut in any shape on demand. There are at least three major changes taking place: one is the impact of IT technology; another is the improvement in quality with high pressure gas cutting and the third is the development of thick section cutting.

Impact of IT technology: The thin section cutting market has been greatly affected by the changes in communication technology. The use of email or fax allows designs to pass swiftly from the designer to the cutting job shop. The improvement in computer software enables designs to be translated into machine code rapidly. One of the UK leading job shops, Micrometric, has 30% of its turn over required to be processed within 3 days. For specials it can be done in a few hours. This frees manufacturers from the tyranny of large runs that are needed to justify traditional pressed or punched parts. Also the ability to make high quality cut edges with a swift turn around time has affected the design of a number of articles. Thus one of the impacts of the laser is to affect manufacturing philosophy. The approach to manufacturing is further affected by the development of special laser cutting machines for tube cutting while others are designed for "lights off" operation.

The improvement in computer programming of CNC cutting machines (e.g. reading ahead of information blocks) and the introduction of linear bearings as opposed to ball screws has raised the cutting speed so that a laser flat bed cutter can now compete with a standard punch press, and yet have the versatility to change the hole shape for every hole.

High pressure gas cutting: The recent trend is to move away from oxygen cutting, which may cause some minor oxidation effects on the edge of stainless steel and other special materials, to high pressure nitrogen cutting ($\approx$ 14 bar). This requires considerable quantities of nitrogen. Smaller job shops are installing their own nitrogen generating facilities based on the pressure swing absorption principle (PSA). The alternatives of multiple cylinder packs (MCPs) or bulk liquid storage occupy too much space and are more costly.

Thick section cutting: One significant development has been the ability to cut thicker sections in both steel and aluminium with dramatic impact on ship building and aircraft frame manufacture. In ship building the lack of distortion achieved by using a laser saves hours of levelling by hammers. The high brightness fibre laser has a phenomenal piercing rate, but a narrow kerf necessitating beam spinning or some such to allow for the removal of the melt during cutting.

One variation on the laser cutting process is the LASOX process in which the laser acts as a match to the oxygen cutting process. This allows very thick section cutting with square edges and greatly reduced cutting time, mainly due to the high pierce rate. For example, a 1 kW laser can cut 80mm thick steel by this process with a kerf width similar to that for oxygen cutting.

Developments in welding

The optical system: Some 20 years ago the speed and quality of laser welding made tailored blank welding a possibility. This process rapidly altered the whole approach to automotive pressed part manufacture [4]. Today fibre optic delivery coupled to an articulated robot arm has proved to be ideal for welding body in white applications for the car industry. The high brightness beams from a fibre laser allows working at a distance due to the greater depth of focus, which in turn means that beam steering can be via galvanometer mirrors instead of moving the whole optical system. A coupled galvanometer beam deflection optic mounted on an articulated robot arm has been tested by the Welding Institute in Cambridge, UK. The high brightness of the beam has allowed welding of aluminium. CO_2 lasers are currently used in welding stiffener stringers onto fuselage skins for such planes as the latest A380 Airbus. Pulsed welding is showing improvements over CW welding for some applications.

Hybrid laser-arc processing: The need for high speed and yet a wide weld fusion zone for fit up reasons has seen a revival of interest in hybrid laser welding, which is the combination of an electric arc or plasma with the laser beam [5]. The hybrid process is being used successfully in welding stiffeners to deck sections for ships. The product is lighter and yet as strong as the thicker plates used previously. The process has been approved by the Classification Societies for ship building. The remarkable thing is the huge reduction in distortion achieved by using a laser as opposed to TIG or MIG welding [6].

Monitoring and control: Tailored blank welding, stiffener welding and most laser welding applications are swift and need to be automated. Laser weld monitoring has been developed mainly using seam trackers, auto focus devices and sometimes plasma sensing systems to monitor the weld quality. In one example from the TWI, Cambridge, they have not only measured the seam position but also the gap width and used this data to control the process speed. This "adaptive control" will surely be developed further [7].

Developments in laser based additive manufacture.

History: Rapid prototyping (RP) systems based on additive fabrication began to emerge in the mid 1980s. The process is to design a 3D article in a CAD package, then slice it within the computer programme and feed the sliced data via a translator into a CNC machine that generates the article layer by layer. The first such piece was made in 1892 by Blanther to produce relief maps by stacking wax plates, which followed the contour lines. Since then stereolithography based on monomer polymerisation via a scanned ultra violet laser dominated the market in 1980s, followed swiftly by the Selective Laser Sintering (SLS) process developed at the University of Texas in Austin by Carl Deckard in the early 1990s. Today additive manufacture is used by most manufacturing industries from automotive, medical, architectural, aerospace, jewellery and academic use; but many of these now do not need a laser. 3D printers are clean, easy to use, small, have good quality products and the equipment is cheap, costing around £20k. They can be found in design studios, colleges and schools. In Stereolithography the laser has been largely replaced by an arc lamp. The laser has initiated many processes from annealing integrated circuits to RP in which cheaper routes have displaced it. The coming of cheaper lasers in the form of diodes may well alter this vulnerability of the laser.

Rapid Tooling (RT) and Rapid Manufacturing (RM): However, the direct casting of 3D objects by layer deposition through powder melting is still the preserve of the laser and will stay so until an alternative finely focussed energy source can be found – which is unlikely. Currently in Rapid Tooling (RT) and Rapid Manufacture (RM) the laser is not seriously challenged – friction and forging technologies such as Ultrasonic Material Consolidation (Solidica, US) and the Cold Dynamic Manufacturing (Cambridge University) are unlikely to compete in speed and quality.

Through these processes the advantages of mass production can be questioned and localised, sustainable manufacturing where economies of scale no longer exist considered instead. Could this be a cottage industry of the future? At present the equipment and computing back up are expensive, but even that can be managed by sending designs to a few well equipped manufacturing centres, any where in the world, on a job shop basis. In the long run the prices will come down even for CNC machines, as we have seen for computers, with an explosion of demand when it gets to the hobby level.

Developments in marking and engraving

Trend to shorter wavelengths: Laser marking was one of the first applications of the laser. It can be done in various ways: dot matrix scanning; mask imaging or vector marking and the more recent advent of 3D marking in glass blocks by non linear absorption of the beam at the focal point to generate a fine crack pattern. The basic unit for a laser marker is a source, galvanometer steering system and software to control it or a mask imaging system which may use a liquid crystal mask for flexibility of design. The laser source has moved towards shorter wavelengths which can mark directly onto uncoated metals with ease and it can produce colour contrasts on many plastics due to several complex phenomena (e.g. foaming, carbonising and bleaching) none of which can be done with the longer CO_2 wavelength. The shorter wavelength will often be capable of a sharper focus.

High quality beams, currently from end pumped Nd:YAG or vanadate (YVO_4), with very high peak powers (over 100kW during a 6ns pulse) are producing crisp marks. One consequence of using end pumped lasers is that one can gain high efficiencies from some non linear processes such as frequency doubling or tripling. Such a laser can deliver 20W in the infrared, 12W at 532nm (green) and tripled to give 3W at 355nm (near UV). The vanadate option allows high peak powers at high Q-switch frequencies – enabling the maximum speed of marking to be extended, while still overlapping individual pulses to create a visually continuous line [8].

Fibre lasers are becoming available. They are not normally Q-switched in the same way as a rod laser but act as amplifiers for a seed source which is modulated at high frequency. The effect in terms of output is similar with the advantage that the peak power profile is flat with respect to the Q-switch frequency, meaning that the Q-switch frequency can be changed without having to adjust the peak power characteristics. They do however suffer from back reflections owing to their high gain amplification.

Increased speeds: With higher brightness, more power and higher pulse frequency the possible marking speeds have increased and the mechanical galvanometer mirror steering system is becoming a limiting factor; possible acousto-optic deflection may be developed. One of the major new applications benefiting from the higher beam quality (better resolution) and advanced control algorithms (giving real grey scales for each laser spot) is photo-imaging onto plastics for various ID cards; but very high marking speeds allowing marking "on the fly" will surely have an impact on security marking, dating, and hence manufacturing regulations.

Developments in micro processing

Hole drilling: Micro processing is predicted to be the largest growth area for industrial lasers over the next decade. Currently it is used in stent manufacture and drilling printed circuit boards in which it has superseded mechanical drilling. The fine holes possible with the laser have been steadily improved enabling the revolution in the size and functionality of mobile phones. Until recently the potential for some fine work in micro processing has been shown possible in the laboratory but is held back from production due to burrs, recast layers, positive taper, speed and lack of knowledge. The recent improvements in laser technology, especially diode pumped solid state lasers whose powers have increased by an order of magnitude and similarly their beam quality, can now achieve quality processing repeatedly by the correct choice of laser wavelength, pulse duration, focused intensity, shot overlap and in some cases pre-post treatment of the material. Laser drilled holes down to 40μm diameter, holes with negative taper, fluting and shape control have been made. The list of possibilities is now extensive including a hole of 1micron diameter and high aspect ratios >50:1. Percussion drilling at rates of hundreds and thousands of holes per second has led to the study of the mechanical and fluid flow potential of highly perforated sheets for aerospace and other applications – a novel material for engineers.

Short pulses and ablation: Ultra fast lasers (pico-second or femto-second pulses), fibre lasers and disc lasers appear to offer a new processing regime in which considerable research is being committed. The short sharp pulse achieves ablation with little collateral damage and though only a small amount is removed per pulse the high repetition rate makes the overall removal rate interesting for manufacture. Laser ablation is a versatile manufacturing tool and has been used to create micro parts.

Finer Focus: In the nano technology region the steady improvement of integrated circuits, which over some 30 years has followed "Moore's Law" – first postulated in 1965 which states that the number of transistors in a chip will approximately double every 24 months – has been enabled partly through the application of lasers. Chip features are replicated photolithographically on a polished silicon wafer. In the late 1980s a mercury arc lamp filtered for the i-line UV at 365nm allowed the smallest transistor to be 350nm, similar in size to the wavelength. In 1995 deep UV krypton fluoride lasers operating at 248nm were introduced. In 2002 the ArF laser operating at 193nm followed and created a market for photolithography light sources from almost nothing to what is now one of the most valuable sectors in the laser industry worth around $400M per annum. 193nm immersion lithography will allow critical dimensions down to 45nm less than one quarter of the wavelength of the exposure light [9].

The future is to further shorten the exposure wavelength through extreme ultra violet (EUV) which is likely to come from laser generated plasma and will operate at 13.5nm. The laser is leading the way in semi conductor chip manufacture which is transforming our lifestyles through the revolution in information technology.

Developments in surface engineering

Laser surface engineering covers a wide area of potential applications. The lower beam quality required for most surface treatments has led to the use of high powered diode lasers (HPDL) for such applications as hardening, cladding, paint stripping, film removal of ITO from flat screens, hybrid plasma/laser or laser/flame spraying processes for forming functionally graded surfaces, improving surface wettability surface modification, laser shock peening and laser cleaning.

Laser Cladding: Laser cladding and surface coating of engineering materials for improved tribological properties, such as coating with metal matrix composites (MMC) - typically TiC, WC, Si3N4 or SiC embedded in metal matrix of Ti or Ni alloys - can be achieved by blowing metal powder into the laser beam generating something resembling a "metal pencil. Hybrid laser/plasma or laser/flame spraying to produce density graded ceramic coatings, pioneered by Professor Lin Li at the University of Manchester [10], has shown that the wider heating due to the plasma or flame helps to temper the clad layer thus avoiding cracking.

Patterned thin films can be deposited by physical or chemical vapour deposition. One application is the deposition of bioactive films on titanium substrates for improved bio-compatibility for medical implants.

Laser shock peening was at one time a complete novelty with little future, it has come to reality with the introduction of high energy, pulsed lasers. This unusual process depends on the generation of a surface plasma explosion that causes strong compressive pressures on the surface, in the same manner as shot peening. Laser peening however gives a significantly greater depth of hardening, can reach into corners and does not throw shot around that has subsequently to be recovered or removed. In the aero industry there are two new production facilities one in the USA and the other in UK for treating turbine blades. The process improves their fatigue life by a factor of four.

Heat treatment and surface melting is attracting considerable scientific effort. There is considerable work on understanding the corrosion properties of laser treated surfaces and their properties for cavitation and erosion resistance, for example the work in Hong Kong of Dr H.C.Man's group [11]. In Manchester with Prof Lin Li there is work on improving the wettability of surface by laser treatment [12]. Through this process, similar to laser cleaning, it has been found that surfaces not only become more biocompatible but also they can be soldered without needing flux.

Laser Cleaning: A pulse of laser light can remove lightly adhering material from a surface [13, 14]. The attraction of the process is the lack of water or chemical sprays with reduced dust and noise. It is an environmentally friendly process. The applications include cleaning IC packages, resin removal from PCBs, carbon removal from Kapton, cleaning field emitter arrays, silicon wafers, disc drive heads, archival paper documents, rust removal from steel, residual drug removal from metal containers, cleaning art work and statuary, removal of radioactive contamination from nuclear facilities, paint stripping and graffiti removal.

Surface texturing is just being appreciated as a possible new outlet for improving tribological properties of mechanical components, improving cell integration for medical implants, patterning ITO (Indium Tin Oxide) coatings for Liquid Crystal Display (LCD) screens. Micro surface texturing looks like playing an important part in the new surge in medical understanding.

Conclusions

The subject of laser material processing: It is apparent that the subject of laser material processing is vibrant and on the verge of moving into new technological areas opened up by the new generation of high brightness lasers and special lasers capable of ultra short pulses.

Its application: On the manufacturing front the laser is offering an alternative to mass production and long production runs. It is also providing the tools for a totally new area of industrial design from tailored blanks to fine detailed cutting, marking, texturing and 3D manufacture in a single machine. Could this be the basis of a new cottage industry?

Its management: For leaders in society the laser has given us a new form of industrial energy for which engineers need to be properly trained. Universities and Colleges should teach the subject of optical engineering.

References

1. Steen W.M. (2003) Laser Material Processing 3rd Edition, Springer Verlag, Berlin, London 408pp.
2. Ireland C. (2005) Developments in high power laser sources, Industrial Laser User Issue 40, Sept. 2005 pp18.
3. Powell J. (1993) Laser cutting, Springer Verlag, Berlin, London, 246pp.
4. Azuma K., Ikemoto K. (1993) Laser welding technology for joining different sheet metals for one piece stamping, Laser Applications for mechanical Industry Proc NATO ASI Erice, Scicily, Kluwer Academic, Netherland 1993, pp219-233.
5. Steen W.M. (2006) Hybrid Laser-arc Processing, Proceedings of PICALO Melbourne, Australia, paper 501.
6. Wegener K. (2005) Special purpose machinery for laser and hybrid welding of large parts. Part 1: overlap and butt welding, Industrial Laser User 2005 S 38-41.
7. Hilton P (2005) Developments in laser welding, The Industrial Laser User Issue 40 Sept. 2005 pp20.
8. May A. (2005) Developments in laser marking and engraving, Industrial Laser User issue 40 pp22.
9. Gower M. (2005) Developments in the IT sector, Industrial Laser User Issue 40 pp27.
10. Li J.F., Li L., Stott F.H. (2004) Multiple surface coatings of refractory ceramics prepared by combined laser and flame spraying, Surface Coating Technology vol180-181 C, 2004 pp499-504.
11. Man H.C., Cui Z.D., Yue T.M. (2002) Surface characteristics and corrosion behaviour of laser surface nitrided NiTi shape memory alloy for biomedical applications, J. Laser Applications 14(4) 242-247.
12. Hao L., Lawrence J., Li L. (2005) The wettability modification of bio-grade stainless steel in contact with simulated physiological liquids by means of laser irradiation, Applied Surface Science Vol 247, No. 1-4, pp453-457.
13. Luk'yanchuk B. (ed.) (2002) Laser Cleaning, World Scientific Publishing, Singapore (ISBN 981-03-4941-1) 466pp
14. Lee J.M. (ed) (2002) Lasers and Cleaning process, Hanrimwon Publishing, Korea (ISBN 89-85670-87-5) 353pp.

此为试读，需要完整PDF请访问：www.ertongbook.com

WELDING WITH STRONGLY FOCUSABLE LASERS UP TO 6KW

Friedrich Dausinger[1] and Jan Weberpals[2]

[1]Institut f黼 Strahlwerkzeuge (IFSW) and [2]Technologiegesellschaft f黼 Strahlwerkzeuge (FGSW), Pfaffenwaldring 43, 70569 Stuttgart, Germany

Abstract

The new diode-pumped disk and fibre lasers found much attention, recently. Both combine the main advantages of the conventional workhorses for laser welding: high efficiency like CO_2 and short wavelength like Nd:YAG (enabling beam guiding through fibres). For the first time solid state lasers with more than 1 kW of mean power reach to the focusability level of CO_2-lasers.

This contribution presents results of welding metal sheets with disk lasers offering output power up to 6 kW. The advantages of strong focusability will be discussed in detail. Special attention will be given to high aspect ratio welding. A comparison with results obtained with a fibre laser will be made, as well.

Introduction

In the past years lasers have evolved to important tools for industrial manufacturing technologies. High processing speed and quality, low heat load and very high flexibility are the most important advantages of laser welding. Although today's lamp-pumped cw-Nd:YAG-lasers are more expensive, have lower focusability as well as lower efficiency than CO_2-lasers they have found an increasing number of applications, especially for cw-welding of 3d-structures. The reason for this is their short wavelength: the beam can be transported via optical fibers, which allows high flexibility and accessibility as well as lower costs for the handling device. In addition, the shorter wavelength of YAG-lasers in comparison with CO_2-lasers brings along advantages for the process such as higher absorptivity in metals and lower sensitivity to laser induced plasma.

Regarding these aspects and driven by market and customer requirements, latest developments are aimed at reducing the above mentioned disadvantages of lamp-pumped solid state lasers. Lasers of this new generation are the diode-pumped thin disk laser and the fiber laser. The concepts lead to higher efficiency and higher focusability at the same time. Focusability is understood as the ability to achieve a small focus diameter with a given optical element. It is defined by the inverse beam parameter product (BPP) [1]:

$$\text{focusability} = \frac{1}{\text{BPP}} = \frac{4}{\theta_L \cdot d_L}. \qquad (1)$$

In [1, 2] it has been shown that, in case of low welding speed (v = 2 m/min), the welding depth is nearly independent on focus diameter. At high enough welding speed ($v \geq 6$ m/min), however, the curves of welding depth lie close together when plotted over the beam parameter ratio (BPR), defined as laser power P_L divided by the focus diameter d_f. In this regime, the welding depth scales mainly with the BPR which means that the influence (and importance!) of the focus diameter is as strong as that of power [2].

Experimental Set-Up

The experiments on the laser welding process regarding the influence of the focus diameter are accomplished with three different laser systems, the lamp-pumped solid-state laser (LPL), the diode-pumped thin disk laser (TDL) and the fiber laser (FL). The lamp-pumped system is characterized by a BPP of 25 mm·mrad and an overall efficiency of 1-5 %. Due to the direct dependence of the focus diameter on the beam parameter product of the laser, this device will be used for the realization of focus diameters from 600 祄 down to 300 祄.

With a beam parameter product of 6 mm·mrad (TDL), which is four times better than a conventional lamp-pumped laser, optical fibers with core diameter of 150 祄 can be used. The very strong focusability of the fiber laser (BPP ~ 2,5 mm·mrad) allows fiber diameters down to 50 祄. Table 1 summarizes the focusing conditions realized for the experimental investigations.

Table 1 Focus diameters achieved by different core diameters of the optical fiber (d_c) and focal lengths of the focusing lenses (f_f). The focal length of the collimation is always f_c = 200 mm.

d_f	laser	d_c	f_f	imaging	div. angle

[祄]		[祄]	[mm]	ratio	[癩
50	FL	50	200	1:1	5,71
75	FL	50	300	1:0,67	3,82
100 *	FL	50	300	1:0,5	2,86
75	TDL	150	100	1:2	11,31
100	TDL	200	100	1:2	11,31
150	TDL	150	200	1:1	5,71
200	TDL	200	200	1:1	5,71
300	LPL	600	100	1:2	11,31
450	LPL	600	150	1:1,3	7,59
600	LPL	600	200	1:1	5,71
* f_c = 150 mm @ d_f = 100 祄 (FL)					

Welding Experiments

Influence of focus diameter on welding depth

The welding depth is significantly affected by the focus diameter because with its reduction the average intensity in the focus will increase. Figure 1 describes the welding depth for steel and aluminium at varying focus diameters which can be realized with the different laser devices in dependence of the welding speed. The welds are performed in steel and aluminium as bead on plate welds at a laser power of 3 kW.

The diagrams show for both materials a considerable influence of the focus diameter on the welding depth. The three curves representing the realized focus diameters with the lamp-pumped laser clearly show the dependences mentioned in the introduction. By changing to the thin disk laser with focus diameters from 200 祄 down to 75 祄 an unexpected behavior became evident: Both figures show the trend of an increase of the welding depth for v > 6 m/min with the reduction of the focus diameter which, however, stopped at d_f = 150 祄 . Unexpectedly, for focus diameters of 100 祄 and 75 祄 the penetration became less [3]. On the one hand the welding depth can be increased by using the fiber laser to realize focus diameters smaller than 100 祄 . However, obviously the same limited factor involved a decrease in the welding depth at less focus diameters ($d_f \leq$ 75 祄).

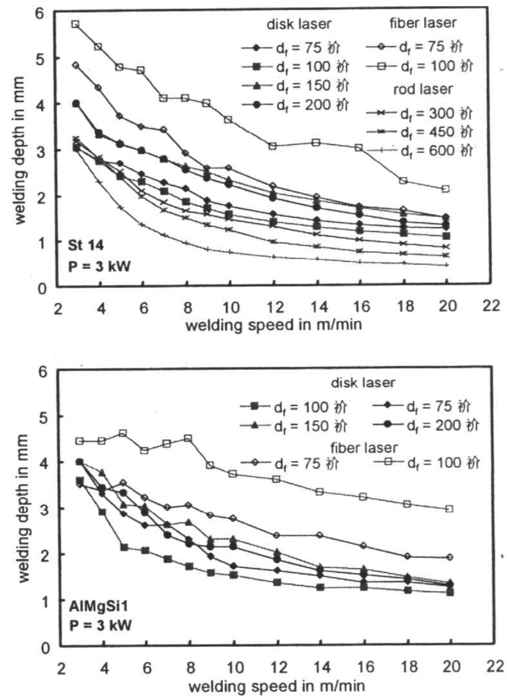

Figure 1 Welding depth as a function of welding speed for focus diameters realized with the different laser devices in steel (above) and aluminium (below).

The question now arises what mechanisms come into action which reduce the welding depth. In searching for possible causes a first answer can be expected from the investigation of the cross sections of the welds which are representative for the process efficiency defined as the product of energy coupling efficiency and thermal efficiency [4].

Influence of the focus diameter on cross sectional area

Looking for possible causes of this phenomenon, in the first place, the idea suggests itself that a laser-induced plasma could change the conditions for energy coupling by absorption and refraction. In welding with CO_2 - lasers the strong influence of shielding gases, especially helium, on the plasma formation is well known. It is already shown that such mechanisms can be excluded by using a thin disk laser with P = 3 kW @ d_f = 75祄 [5]. Figure 2 clearly shows that even the increased intensity at d_f = 50 祄

does not produce at velocities beyond 5 m/min a disturbing laser-induced plasma as well.

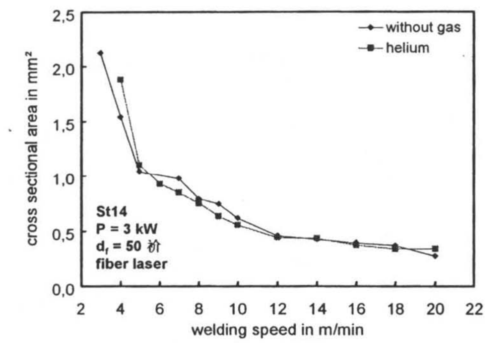

Figure 2 Cross sectional area is independent of the shielding gas even at d_f = 50 祄 @ P_L = 3 kW.

Figure 3 represents the influence of the focus diameters (thin disk laser and fiber laser) on the cross sectional areas as a function of the welding speed. The results are shown for steel but aluminium displays the same feature. Additionally the larger focus diameters (LPL) show a comparable trend regarding the melted volume of the seam [5].

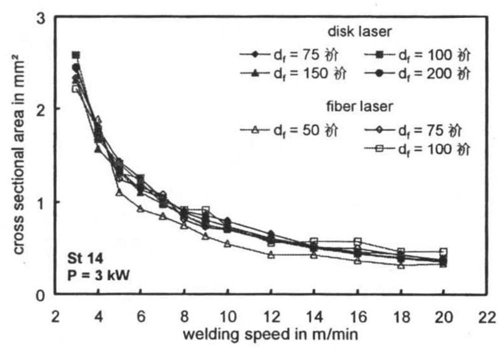

Figure 3 Cross sectional area as a function of the welding speed for different focus diameters.

The examination of Figure 3 indicates that the cross sectional area is independent of the focus diameter. This means that the process efficiency has always the same value, but this behavior will be discussed later on. Against this background it appeared likely that the focal conditions (see Table 1) do influence the shape of the weld seam. In fact, above a welding speed of 6 m/min this can be seen in Figure 4.

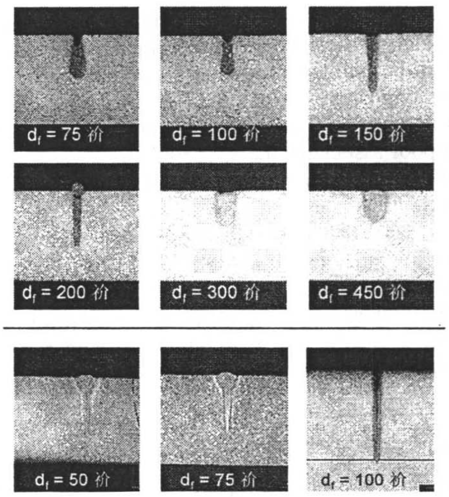

Figure 4 Cross sections for the focus diameters up to 450 祄 (TDL and LPL) and realized with the fiber laser (below) at a welding speed of 9 m/min in steel.

The seams with the largest welding depth realized with the disk laser (d_f = 150 祄) exhibit a slender shape which is attributed to the low divergence of the focused beam. This is a consequence of its improved focusability and the imaging ratio of 1:1; the half divergence angle is θ_0 = 5,71? (f_c = 200 mm, f_f = 200 mm). To get smaller focus diameters, the imaging ratio had to be changed to 1:2 (f_c = 200mm, f_f = 100mm). This means that the divergence angle was doubled to θ_0 = 11,31? Additionally, the flanks of the corresponding seams in Figure 4 show the same angle as the freely propagating laser beam. Apparently the seam is essentially influenced by the divergence angle because it affects the distribution of lines with constant power density (see Figure 5). That means that at smaller focus diameters the welding depth is limited by the divergence angle. Using the fiber laser this effect is also visible by investigating the cross sections in Figure 4. A reduction of the focus diameter leads to an increase of the divergence angle at the same time (see Table 1). Due to this there will be an extremely slender shape at d_f = 100 祄 (θ_0 = 2,86? enabling an increase in the penetration depth. According to this a smaller focus diameter yields less welding depth but at the same time a widening of the seam.

On the other hand, the focal area controls the shape of the seam with large focus diameters ($d_f \geq$ 300 祄). Due to this there will be a shape in form of a "U" in this focus diameter range.

Because of the mentioned influence of the lines with constant power density on the reachable welding depth ($d_f \leq 200$ 祄) their effect should be discussed a little more in detail. They are defined by the distribution of the freely propagating laser beam and run rotation symmetrical along the beam axis [6]. Particularly for steel it is assumed that the limitation of the melt pool associates the shape of the vapor capillary (small diffusion length due to less thermal conduction) because it is appointed by the lines with constant power density. The distribution of these lines is calculated for different fixed quotients E/E_0. To get the lines with constant power density at constant power density E they are normalized on the smallest power density E_0 at the focus ($d_f = 600$ 祄) and shown in Figure 5.

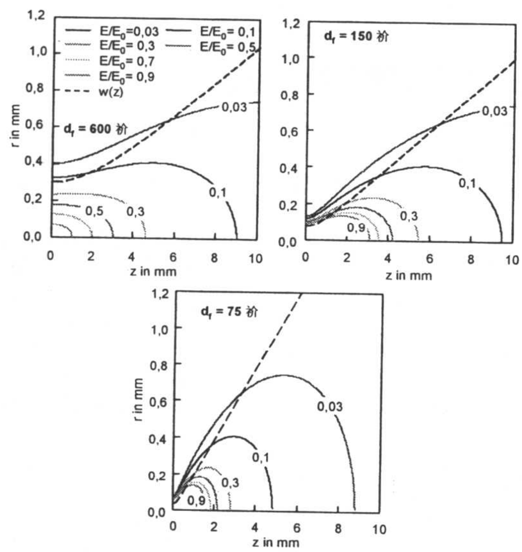

Figure 5 Calculated distribution of lines with constant power density as well as the free beam propagation w(z) at varying focus diameters at normalized power density E_0 (Gaussian mode).

Assuming that at $E/E_0 \approx 0{,}3$ the line with constant density characterize the vaporization line the different seam geometries with their appending divergence angle can be deduced. At the largest focus diameter ($d_f = 600$ 祄) the line with constant power density (vaporization line) propagates parallelly along the beam axis and affords a shape in form of a "U" (see Figure 4). At minor focus diameters ($d_f \leq 200$ 祄) and associated increasing divergence the calculated distribution of lines with constant power density exhibit an increased bulge. At first the welding depth can be raised at $d_f = 200$ 祄 . But as a result of the increasing bulge at $d_f = 75$ 祄 the welding depth became less and develops a drop shaped seam at which the shape approaches the divergence of the focused beam. This shows that the formation of the seam is essentially influenced by the divergence angle because it affects the distribution of lines with constant power density.

Influence of the divergence angle at focus diameters smaller than 200 祄

As can be concluded from these results the divergence angle obviously plays a role in determining the shape of cross section with focus diameters smaller than 200 祄 . To demonstrate this effect in a direct way, the divergence angle at constant focus diameter has been varied by changing the imaging ratio and the core diameter of the optical fiber. In this way three different angles for a focus diameter of 100 祄 have been realized, see Table 2.

Table 2 Combination of core diameter and imaging ratio to get different divergence angles at $d_f = 100$ 祄 .

d_c [祄]	f_c [mm]	f_f [mm]	imaging ration	d_f [祄]	div. angle [癩
200	200	100	1:2	100	11,31
150	150	100	1:1,5	100	8,59
50	150	300	1:0,5	100	2,86

The influence of the different divergence angles on the welding depth for steel and aluminium are clearly seen from Figure 6. The continuous decline of the divergence of the focused beam affects the lines with constant power density in such a way that the welding depth raised in the whole range of applied welding speed.

For lower welding speeds ($v \leq 6$ m/min), where heat conduction plays a major role, the curves approach each other especially for aluminium. For high welding speed the smallest divergence angle leads nearly to a doubling of the welding depth for the both materials.

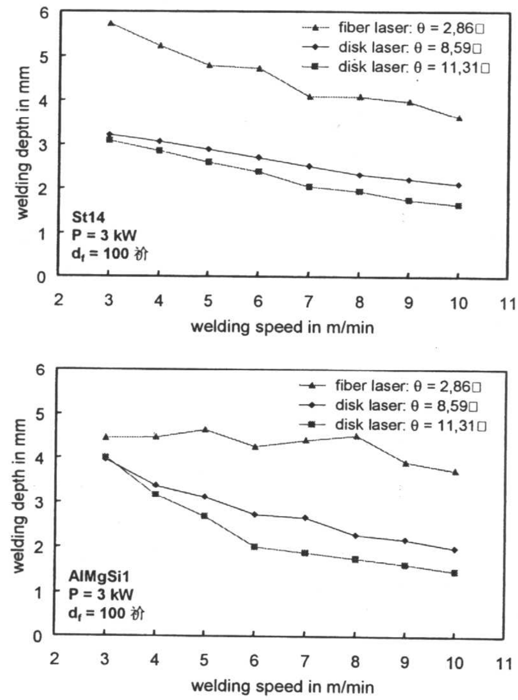

Figure 6 Welding depth as a function of the welding speed for the three divergence angles in steel (above) and aluminium (below) (P_L = 3 kW; d_f = 100 祄).

The considerable influence of the divergence angle on the welding depth and the shape of the seam at the same focus diameter of 100 祄 can bee seen in Figure 7. For both materials the decrease of the divergence of the focused beam yields an increase of the welding depth and a decrease of the seam width at the same time. This relationship leads to a constant cross sectional area of the weld seam independent of the divergence angle at constant focus diameter. The impression of a constant cross sectional area which is obvious in Figure 7 is shown in Figure 8 for steel in more detail. If only the divergence angle is the varied parameter the energy per section and therewith the cross sectional area is at the same value. That means that in the investigated parameter range the process efficiency of keyhole welding is in fact independent of the focusability of the laser device [5].

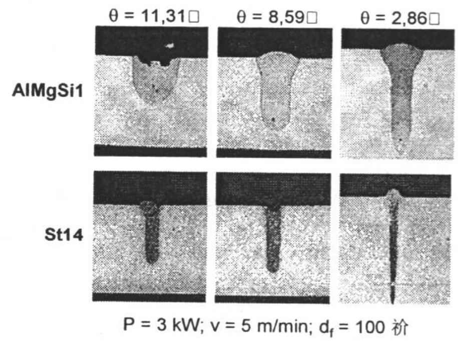

Figure 7 Cross sections for the focus diameter d_f = 100 祄 at varying divergence angles at a welding speed of 5 m/min in steel and aluminium.

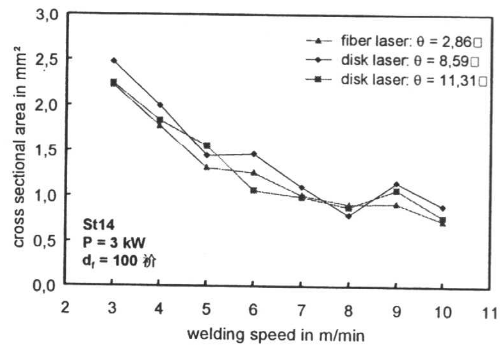

Figure 8 Cross sectional area as a function of the welding speed for the three divergence angles in steel (P_L = 3 kW; d_f = 100 祄).

Dependence of welding depth on focus diameter

At this point the dependence of welding depth on $1/d_f$ as mentioned in [1, 2] shall be examined for the results obtained in the present experiments. For two representative welding speed values and both materials, steel and the aluminium, Figure 9 summarizes the findings: For diameters down to 200 祄 the welding depth is in fact proportional to $1/d_f$ in accordance with earlier statements. At about 150 to 200 祄 , however, a rather abrupt change becomes evident leading to even a decrease in welding depth. That could be explained with the intensity distribution along the beam propagation. It is shown that, in conjunction with very small focus diameters, the divergence angle of the focused beam does play a considerable role in the way energy is deposited under these conditions. Along this line clear evidence is given that, by reducing the divergence of the focused beam (e.g. by a lower beam parameter product), the welding depth can be raised. Therefore, with a further reduction of the beam parameter product it appears possible to obtain an additional increase of the welding depth.

Recent experiments with a 4 kW fiber laser allowed the further reduction of the divergence angle as a consequence of the lower beam parameter product of the laser device (BPP ~ 2,5mm·mrad). The stronger focusability enabled a divergence angle of about 2,86? at a focus diameter of 100 祄 . The resulting increase is shown for the focus diameters of 100 祄 and 75 祄 (θ_0 = 3,82? in Figure 9. Additionally the results achieved by a focus diameter of 50 祄 (θ_0 = 5,71? are shown in that figure.

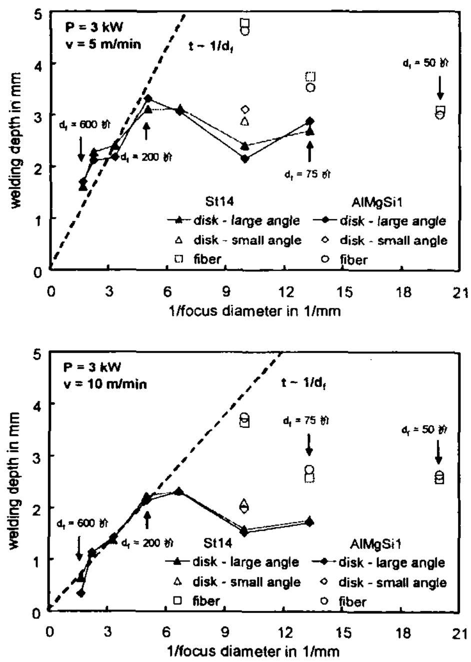

Figure 9 Welding depth for steel and aluminium as a function of the inverse focus diameter at a welding speed of 5 m/min (above) and 10 m/min (below) at P_L = 3 kW.

Influence of the Focusability on the Process Efficiency

In addition to the influence of the focusability on the seam geometry also its importance on the process efficiency is useful for the comparison of the laser devices. Figure 10 show instead of the process efficiency the specific melt pool volume (proportional to each other) as a function of the aspect ratio of keyhole (welding depth/focus diameter).

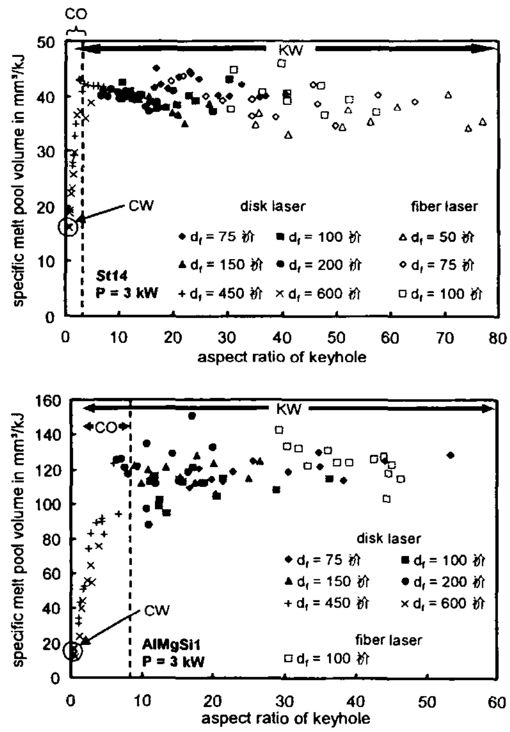

Figure 10 Specific melt pool volume of steel (above) and aluminium (below) as a function of the aspect ratio of keyhole at varying focus diameters (Keyhole Welding (KW), Cross Over (CO), Conduction Welding (CW)).

Figure 10 demonstrate the specific volume as a function of the aspect ratio of keyhole (A_K) for steel in the upper diagram. Because there is no changing of the aspect ratio (A_K = 0,5) during conduction welding all the results are concentrated on one point.

The range from shaping a lentoid cross section at A_K = 0,5 to A_K = 3 is called the cross over (CO). For a focus diameter of 450 祄 at v > 10 m/min and d_f = 600 祄 at v = 6 m/min the specific volume increases from about 16 mm?kJ up to 40 mm?kJ when passing trough the cross over. Minor changes of the process parameters (e.g. welding speed and/or laser power) in the range of the cross over are leading to marked variations of the welding result Due to the fact that already at the cross over a vapor capillary is formed this range belongs to the keyhole welding as well.

Beyond the CO region the specific volume remains essentially constant at a value of about 40 mm?kJ. With a focus diameter of 50 祄 (FL) the aspect ratio

此为试读，需要完整PDF请访问：www.ertongbook.com