第 38 卷 第 8 期
2017 年 8 月
焊 接 学 报
TRANSACTIONS OF THE CHINA WELDING INSTITUTION
Vol. 38 No. 8
August 2017

# 铝合金静止轴肩搅拌摩擦焊组织非均质性对接头力学性能的影响

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摘 要：对 6061-T6 铝合金静止轴肩搅拌摩擦焊( stationary shoulder friction stir welded，SSFSW) 接头组织非均质性与力学性能的相互影响进行了定量分析. 结果表明，SSFSW 焊接接头存在明显的组织非均质性，表现在晶粒尺寸及形状、沉淀相种类及分布形态不同，其中沉淀相析出不同是影响力学性能差异的主要因素. 由于组织非均质性导致紧邻焊核区的热影响区软化严重，其硬度和抗拉强度在接头区域最低，分别为母材的 60% 和 72%，为接头最薄弱部分. 由于沉淀强化和晶粒细化效应，焊核区的强度与塑性最好，而抗拉强度和断后伸长率分别达到母材的 88% 和 215%. 随着与焊核区距离的增加，热影响区抗拉强度和屈服强度逐渐增加，断后伸长率不断降低.
关键词：6061-T6 铝合金; 静止轴肩搅拌摩擦焊; 组织非均质性; 力学性能
中图分类号：TG 453.9 文献标识码：A doi：10.12073/j.hjxb.20150808004

## 0 序 言

静止轴肩搅拌摩擦焊( SSFSW) 是英国焊接研究所在传统搅拌摩擦焊( friction stir welded，FSW) 基础上提出的一种新的焊接方法，其搅拌工具由旋转搅拌针和在材料表面滑动的静止轴肩组成，焊接过程中全部摩擦热量则完全由高速旋转的搅拌针产生[1-2]. 在 SSFSW 焊接过程中由于搅拌针剧烈作用，焊缝区域经历了较大热塑性变形，这种局部摩擦热与材料挤压流动使焊缝附近微观组织产生非均质性，势必对焊接接头宏观力学性能产生显著影响.

文献[3]对 2219-T87 铝合金传统 FSW 接头组织、硬度、冲击韧性和强度的不均匀性进行了分析，并指出 FSW 接头的非平衡组织结构导致了接头性能的不均匀性. 由于 SSFSW 热量全部由搅拌针产生，其热输入更为集中，沿板厚更为均匀，应有利于降低接头局部组织非均质性，但如何定量分析 SSFSW 焊接接头各区域的显微组织非均质性与硬度及力学性能的相互影响未见到详细研究报道.

文中结合 6061-T6 铝合金 SSFSW 试验，采用微小力学试验对接头区域显微组织非均质性对硬度及力学性能的影响进行深入分析，为优化 SSFSW 焊接工艺及改善接头性能提供了重要的试验依据.

收稿日期：2015-08-08
基金项目：五院 CAST 创新基金资助项目( C02016056)

## 1 试验方法

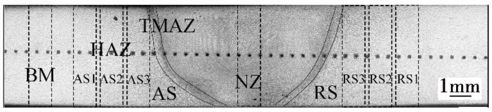
试验材料为 6061-T6 铝合金，试板尺寸为 320 mm × 105 mm × 5 mm. 采用自主研制的静止轴肩搅拌工具完成试板的焊接，搅拌针为带螺纹圆锥形式，根部直径 8 mm，顶部直径 5 mm，长度为 4.9 mm，焊接倾角为 2.5°. 在大量工艺试验基础上，选择优化焊接工艺参数为转速 1 500 r/min，焊接速度 200 mm/min，焊接压力 15 kN.

沿着垂直于焊缝方向切取尺寸为 30 mm × 15 mm × 5 mm 的试样，进行金相分析和硬度测试. 采用 OLYMPUS-GX51 光学显微镜对接头各区域显微组织进行观察. 采用双喷减薄的方法制备接头各区域用于透射电子显微镜观察的试样，使用 Tecnai G2F20 型透射电子显微镜对沉淀相进行观察. 硬度测试沿垂直于焊缝的方向进行测量，载荷 9.8 N，加载时间 10 s，测量间距 0.5 mm.

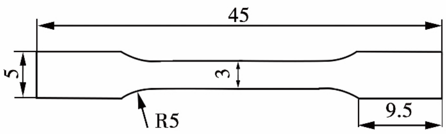
试验取样位置及试样尺寸如图 1 示，沿平行于焊缝长度方向不同位置制备厚度为 1 mm 的微小力学试样，其中试样 AS3，AS2，AS1 和 RS1，RS2，RS3 分别位于焊缝前进侧 AS( advancing side，AS) 和后退侧 RS( reireating side，RS) . 采用 Instron-5848 微小力学试验系统进行性能测试. 试样拉伸断口用 Hitachi-S4800 扫描电镜进行观察.

图 1a 为典型 SSFSW 焊缝的宏观形貌. SSFSW 接头可划分为焊核区( weld nugget zone，NZ) 、热力

影响区(thermo-mechanicall affected zone，TMAZ)、热影响区(heat affected zone，HAZ)和母材区(base metal，BM)四部分，但与传统FSW比较，其TMAZ与HAZ明显较窄，这说明高速旋转搅拌针与母材之间的摩擦变形及热输入明显集中. 图中虚线框位置从左至右分别为BM，AS3，AS2，AS1，NZ，RS1，RS2，RS3. 由图1a可以看出，焊核区形状与锥形搅拌工具基本一致；AS侧母材与焊核区过渡线比较明显，而RS侧过渡线模糊.



(a) 微小力学取样图



(b) 微小力学试样尺寸图(mm)

图1 微小力学取样位置和尺寸图

Fig. 1 Machining sites and dimensions of micro-tensile specimens

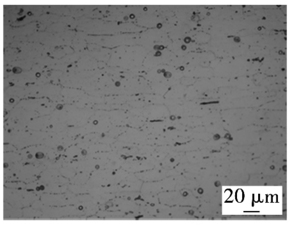
## 2 试验结果及分析

### 2.1 组织非均质性

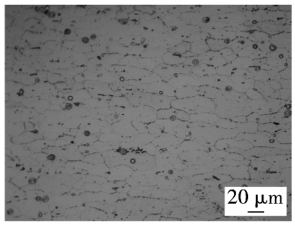
图2为不同微小力学试样取样位置(图1a中实线框)的显微组织. 由图2可以看出，6061-T6铝合金板材晶粒沿着轧制方向伸长，为板条状轧制组织特征(图2a). AS3试样距离焊核区较远，焊接过程中受焊接热循环的影响较小，晶粒尺寸形状与母材晶粒基本相同(图2b). AS2处距离焊核区相对较近，由于受到焊接热循环的影响晶粒有长大趋势(图2c)，但组织仍为板条状特征. AS1试样紧邻热力影响区，由于受到热循环和材料流动产生的挤压作用，组织特征有明显的方向性，晶粒在旋转变形方向上被明显拉长[4](图2d).

焊核区由于在搅拌针的剧烈搅拌作用下，焊接过程中经历了较高温度热循环和强烈热塑性变形并产生动态再结晶，从原始板条状组织转变为细小致密等轴晶组织，晶粒平均直径约为母材晶粒1/5(图2e). 在后退侧最接近焊核区的热影响区RS1试样，在搅拌针旋转挤压作用下晶粒尺寸形状有明显流动趋势外(图2f)，其余逐渐远离焊核区的RS2和RS3试样的晶粒尺寸及形状与AS2和AS3有类似变化趋势(图2g，h).

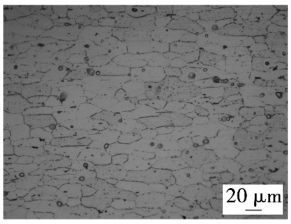
晶粒尺寸及形状的不同会影响不同区域的性能，而热循环和材料流动将对接头不同位置沉淀相种类与分布产生显著影响. 6061-T6为沉淀强化铝合金，主要包括四种沉淀相即GP区、$\beta''$及$\beta'$过渡相、$\beta$平衡相($Mg_2Si$)，其中$\beta''$相是影响力学性能的主要因素.



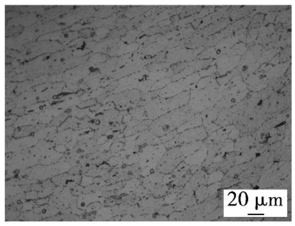
(a) BM位置处组织特征



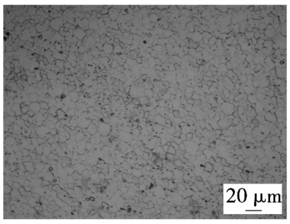
(b) AS3位置处组织特征



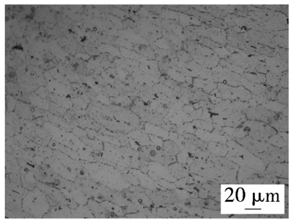
(c) AS2位置处组织特征



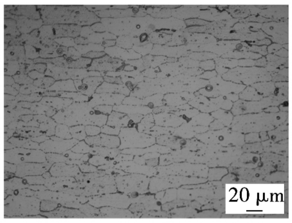
(d) AS1位置处组织特征



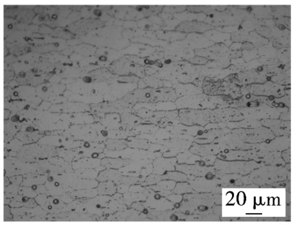
(e) NZ位置处组织特征



(f) RS1位置处组织特征



(g) RS2位置处组织特征



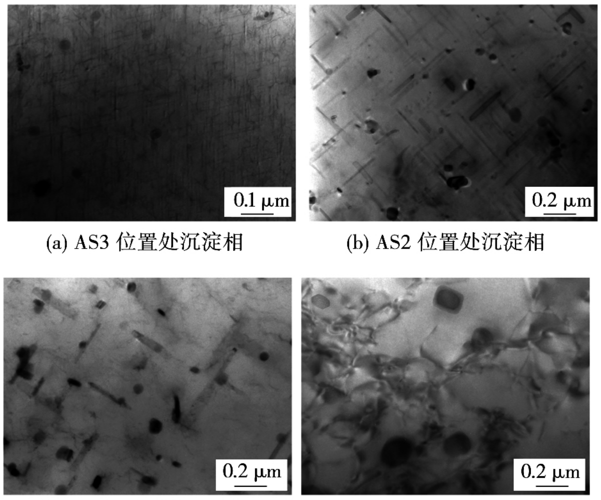
(h) RS3位置处组织特征

图2 SSFSW接头不同位置处的组织特征

Fig. 2 Grain structures for different locations of SSFSW welded

图3为SSFSW接头中AS3，AS2，AS1及NZ区域的透射电镜的组织形貌. 由图3可以看出，在热影响区的不同位置，其沉淀相种类与分布有较大差异. AS3区接近母材而远离焊核区，受焊接热输入影响很小，沉淀相为针状$\beta''$过渡相，其分布均匀且密度较大；随着不断接近焊核区，AS2区受到焊接热输入的影响增大，$\beta''$相开始溶解并析出棒状$\beta'$沉淀相，其分布密度降低；紧邻焊核区的AS1热影响区受热输入影响温度最高，因而$\beta''$相发生完全溶解并析出$\beta'$过渡相，使得沉淀强化作用明显降低而形成软化区. 焊核区原始沉淀相$\beta''$在焊接过程中完全溶解形

成过饱和固溶体，在快速冷却后形成与基体共格的 GP 区. 由此可见，由于焊接热输入和材料形变作用，SSFSW 接头不同区域中晶粒形状尺寸、沉淀相种类及分布有明显差异，这是导致接头不同位置力学性能差异的根本原因.




(a) AS3 位置处沉淀相　(b) AS2 位置处沉淀相

(c) AS1 位置处沉淀相　(d) NZ 位置处沉淀相

图 3　SSFSW 接头不同位置处的沉淀相

Fig. 3　Precipitates at various locations of SSFSW joint

## 2.2　接头硬度分布

图 4 表示 SSFSW 接头试样截面中心线上硬度分布. 由图 4 可以看出，焊前 6061-T6 铝合金经过热处理后强度及硬度均达到最高状态，母材硬度达到 102 HV；焊后由于组织非均质性导致热影响区硬度变化较大，硬度在母材硬度值 60% ~ 90% 之间变化. 热力影响区硬度为母材硬度 70% 左右；而焊核区硬度分布均匀，均在母材硬度 75% 左右.

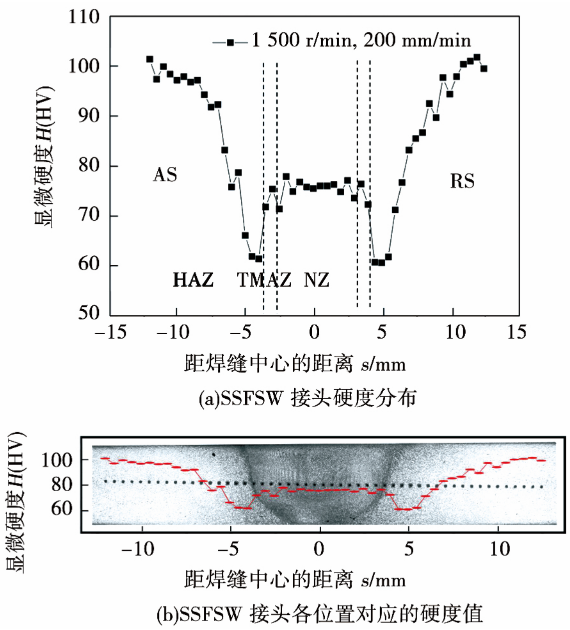



图 4　接头显微硬度分布

Fig. 4　Hardness profiles of welds

焊核区近处热影响区硬度最小，为严重软化的区域，最小值为 60.6 HV，只达到母材的 60%. 原因是在焊接过程中该区域热输入较大，引起该区域的组织粗化、沉淀相转变，导致该区域软化严重. 热力影响区硬度明显增加，原因是该区域材料流动剧烈，引起变形强化，位错密度增加. 焊核区硬度较均匀，硬度值达到母材的 75%. 相对于热影响区、焊核区硬度明显升高，主要是由于高温溶解了沉淀相，冷却时经历了时效过程，沉淀相再次析出，所以焊核区硬度相对较高[5]. 此外，焊核区细小致密等轴晶组织的细晶强化作用，对焊核区硬度的提高有一定作用. 由此可见，由于焊接热输入和材料形变作用，SSFSW 接头不同区域中晶粒形状尺寸、沉淀相种类及分布有明显差异，这是导致接头不同位置力学性能差异的根本原因.

## 2.3　力学性能

### 2.3.1　拉伸性能

图 5 为 SSFW 接头不同区域的拉伸性能.

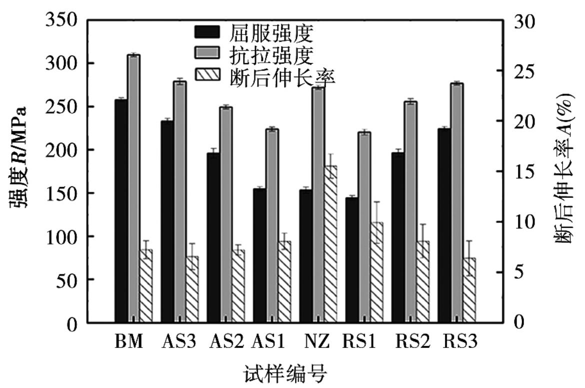



图 5　SSFSW 接头不同区域的拉伸性能

Fig. 5　Tensile properties at different sites of SSFSW joint

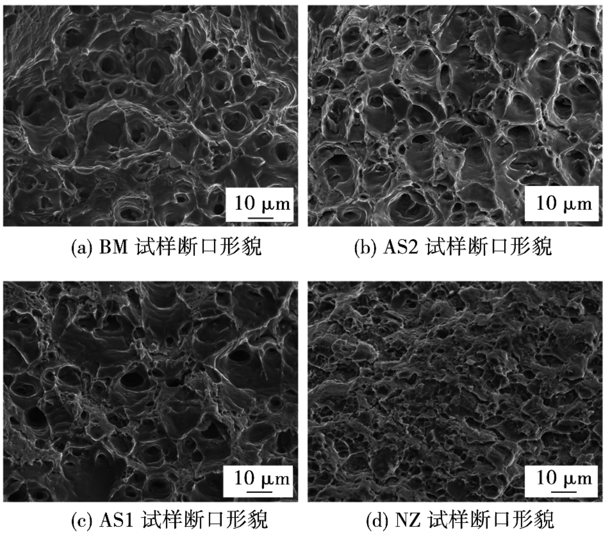
由图 5 可以看出，母材的抗拉强度和屈服强度最高，取自热影响区的 AS3，AS2 和 AS1 试样的抗拉强度分别是母材的 90%，81% 和 72%，焊核区的抗拉强度为母材的 88%. 热影响区各位置试样屈服强度的变化规律与抗拉强度相同，然而焊核区的屈服强度明显较低，只有母材的 60%. 热影响区 AS3，AS2 和 AS1 试样断后伸长率分别是母材的 90%，95% 和 100%，焊核区的断后伸长率在接头区域最高，达到了母材的 215%.

由于 6061-T6 铝合金的强度及力学性能主要受沉淀相种类和分布的影响，接头各区域力学性能与

母材差异主要取决于其组织特征. 焊核区的韧性明显高于其它位置，这是由于焊核区晶粒细化和位错和位错密度增加使得塑性明显增加. 在焊接过程中焊核区热输入较大，引起沉淀相溶解，在冷却过程中焊核区形成过饱和固溶体而没有析出$\beta''$相，因此虽然提高了焊核区的强度，但与母材比仍有软化现象；热影响区各位置受到焊接热循环和材料流动的作用，引起晶粒粗化及原始$\beta''$沉淀相溶解与$\beta'$析出，其强度与塑性产生明显变化. 如 AS1 处由于受到热输入和材料塑性流动的影响较大，晶粒变形明显，沉淀相发生转变，导致抗拉强度和屈服强度最低，是接头性能最弱的区域.

### 2.3.2 断口形貌

SSFSW 接头组织非均质性导致力学性能差异显著，也反映在试样的拉伸断口形貌上. 图6为BM，AS2，AS1 和 NZ 试样拉伸试验后的断口形貌. NZ 和 HAZ 各位置断口形貌均为典型韧窝特征，在部分韧窝底部发现有第二相粒子脱落的现象，断裂方式属于微孔聚集型断裂. BM 拉伸试样断口由大小形状均匀的韧窝组成，且韧窝尺寸大，数量多. 取自 HAZ 的 AS2，AS1 试样拉伸断口主要为较大尺寸的韧窝，且韧窝的数量和母材相比明显较少. NZ 试样拉伸断口由大量韧窝组成，且有明显的变形特征.




(a) BM 试样断口形貌 (b) AS2 试样断口形貌

(c) AS1 试样断口形貌 (d) NZ 试样断口形貌

图6 不同位置拉伸试样的断口形貌

Fig. 6 Fracture surface of tensile specimens

接头各区域的断口形貌与母材有不同程度的差异，NZ 的非均质性较大. 在靠近 NZ 的 HAZ，焊接过程中受到焊接热循环影响较大，部分沉淀相发生溶解，导致大尺寸韧窝数量减少，明显降低了该区域的力学性能. NZ 中粗大的第二相在焊接过程中被破碎，由于搅拌工具的作用更加均匀的分布在 NZ 中，因此，NZ 拉伸断口存在大量尺寸较小的韧窝，从而提高了 NZ 的强度和塑性. NZ 断口中一部分韧窝尺寸较大，在拉伸过程中变形协调能力强，对焊核区的力学性能贡献较大.

## 3 结 论

(1) 6061-T6 铝合金 SSFSW 接头存在明显组织非均质性，主要表现在晶粒尺寸及形状、沉淀相种类及分布形态不同，其中沉淀相析出变化规律不同是影响力学性能差异的主要因素.

(2) 由于组织非均质特征，SSFSW 接头焊缝截面显微硬度分布明显不均匀. 紧邻焊核区的热影响区软化最严重其硬度为母材的 60%，焊核区也有软化，但由于沉淀强化和晶粒细化的作用，其硬度有所恢复，达到母材的 75%，前进侧和后退侧焊缝随远离焊核区硬度具有基本相同变化趋势.

(3) 由于组织非均质特征，SSFSW 接头不同区域力学性能与母材相比存在明显差异. 焊核区强度与塑性最好，其抗拉强度为母材 88%、而断后伸长率可达到母材的 215%；紧邻焊核区的热影响区抗拉强度最低仅为母材 72%、断后伸长率与母材相当. 随着与焊核区距离的增加，热影响区抗拉强度和屈服强度逐渐增加，断后伸长率逐渐降低.

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tion for Special Welding Materials and Technology, Chongqing 400054, China). pp 107 – 110

**Abstract:** Pore defects are the major problem in vacuum electron beam welding. The inducement mechanism and thermodynamic equilibrium mechanism were analyzed from the perspective of force balance condition, and the minimum radius survival conditions for pores in molten pool were proposed. The results showed that the gasification nucleus is an important factor induced bubbles in molten pool from the perspective of bubble dynamics. The bubbles, which don't meet the minimum radius survival condition, do not satisfy the thermodynamic equilibrium condition and therefore can't develop into the pores. The size of the bubbles generated on the wall of middle part of weld depends largely on the gas density in bubble, surface tension of bubble, and overheating of gas-phase components in bubble. The overheating is not only a driving force for bubble stability, but also a main factor determining the bubble size.

**Key words:** vacuum electron beam welding; bubble; pore; equilibrium mechanism; survival condition

**Effect of heat treatments on resistance spot weldability of TRIP 980 steel** WEI Shitong, LU Shanping (Shenyang National Laboratory for Materials Sciences, Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, China). pp 111 – 114

**Abstract:** Cold rolled TRIP 980 steel sheets were resistance spot welded by different welding procedures. The effects of welding current, preheating and postweld heat treatments on the resistance spot weldability were studied. The results show that the increasing welding current increases the nugget diameter and tensile shear strength of spot weld. However, when the welding current is large enough to cause spatter, the nugget diameter and tensile shear strength of spot weld decrease. The preheating process raises the spatter occurring current, which results in larger nugget diameter and tensile shear strength. Under the condition of adding postweld heat treatment to spot weld, when the cooling time between welding current and postweld heat treatment current was larger than 900 ms, the microstructure of weld nugget was improved significantly, which decreased the hardness of weld nugget and increased the tensile shear strength of spot weld.

**Key words:** resistance spot welding; welding parameter; heat treatment; tensile shear property; nugget diameter

**Effect of microstructural inhomogeneity on mechanical properties of stationary shoulder friction stir welded joints for 6061-T6 aluminum alloy** HE Fangzhou[1], YANG Xinqi[1], LI Dongxiao[2], CUI Lei[1] (1. Tianjin Key Laboratory of Advanced Joining Technology, Tianjin University, Tianjin 300072, China; 2. Beijing Satellite Manufacturing Factory, Beijing 100094, China). pp 115 – 118

**Abstract:** The relationship between microstructural inhomogeneity and mechanical properties of the stationary shoulder friction stir welded (SSFSW) joint for 6061-T6 aluminum alloy was investigated. Results show that there is existing obviously microstructural inhomogeneity in the SSFSW joints, which reflected in the different grain size and shape, morphology and distribution of precipitates. It should be noted that the different precipitates is the major factor of the mechanical properties variation. Resulting from the microstructural inhomogeneity, the HAZ which is closed to the NZ was softened seriously, and its hardness and tensile strength were the lowest in the joint, reaching at 60% and 72% of the base metal, respectively. The strength and plasticity of the NZ are the best in the joint because of the precipitation strengthening and fine-grain strengthening, and the tensile strength and elongation of the NZ reach at 88% and 215% of base metal, respectively. With the distance from NZ increasing, the ultimate tensile strength and yield strength of micro-tensile specimens increase, while the elongation of samples decreases.

**Key words:** 6061-T6 aluminum alloy; stationary shoulder friction stir welding; microstructural inhomogeneity; mechanical property

**Effect of heat input on weld appearance for fiber laser welding 6A02 aluminum alloy** XU Fei, CHEN Li, LU Wei, GUO Luyun (Science and Technology on Power Beam Processes Laboratory, Beijing Aeronautical Manufacturing Technology Research Institute, Beijing 100024, China). pp 119 – 123

**Abstract:** The fiber laser beam with high power density is used for welding 6A02 aluminum alloy with 1.0mm thickness. And the effects of heat input on weld macrography, structure and properties are studied. The results show that the stable fully penetration weld could be obtained when the heat input is controlled in the range of 8-12 J/mm and the welding speed is very high. The typical cross-section of the welds always presents near X shape. The characteristic of the welds could reduce the nonuniformity of welding temperature field. It also could reduce welding buckling and deformation. The columnar microstructure is formed near the fusion line. The mixed microstructures, including columnar grains and equiaxed grains, distribute in the center of the weld. The transition from columnar microstructure to mixed microstructures can be found from the fusion line to the weld center. With the heat input reduced, the microstructures of the weld zone are tendency to fine, the soften phenomenon near the fusion line is helpful to weak, the microhardness of the weld zone and the tensile strength of the joints are increasing slightly.

**Key words:** fiber laser welding; weld appearance; microstructure; microhardness; tensile properties

**Impact on welding pool shape under combined effect of magnetic field and active agent** LIU Zhengjun, WANG Xiaohui, SU Yunhai (Materials Science and Engineering, Shenyang University of Technology, Shenyang 110870, China). pp 124 – 128

**Abstract:** In order to study the combined effect of magnetic field and active welding influence on the welding pool of liquid metal flow pattern, the paper established the moving heat source under the action of three-dimensional transient mathematical model of magnesium alloy TIG welding. By using fluent software and its secondary development function to simulate the welding pool temperature field and velocity field under the effect of single magnetic field, single active welding and the combined effect of both. The simulation results show that liquid metal in the welding pool was directed clockwise rotation under the effect of single magnetic field, velocity field presented asymmetrical bimodal distribution, maximum speed biased the pool side. Under the effect of single active welding liquid metal in the welding pool formed outside-in convection mode, which scour the bottom of the pool to increase penetration. The fluid flow is more complex under the combined effect of magnetic field and active agent. The liquid metal flow near the pool surface is mainly affected by surface tension. The liquid metal flow inside the pool is mainly affected by external electromagnetic force.

**Key words:** electromagnetic force; surface tension; temperature field distribution; velocity field distribution