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烧结时间对自钎剂钎料显微组织和力学性能的影响

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摘　要： 采用热压烧结法制备了 Al88Si 自钎剂钎料环，研究了不同烧结时间条件下自钎剂钎料的显微组织和 3003 铝合金钎焊接头显微组织及力学性能. 结果表明，钎料显微组织为 AlSi 基体、块状初晶硅相和颗粒状 $KAlF_4$；随着烧结时间的增长，钎料中钎剂活性降低. 3003 铝合金钎焊接头钎缝组织由 α_{Al} 固溶体和针状共晶硅相组成；随着烧结时间的增长，钎料的流铺性能越来越差，钎焊接头中裂纹、固体夹杂、未钎满、孔穴等缺陷逐渐增多，钎焊接头强度降低.

关键词： 自钎剂钎料；铝及其合金；铝硅钎料；烧结时间
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0 序　言

铝合金由于优良的物理化学性能，良好的加工、表面处理与耐腐蚀性能[1]，加之地壳中储量丰富(8.0%，仅次于氧和硅)，在现代工业材料中占有重要的地位. 随着资源短缺、环境恶化的加剧，在航空航天、建筑、电气、汽车和船舶等行业以铝代铜、以铝代钢[2]取得了可喜的成绩. 钎焊作为一种可靠连接方式，在铝合金发展应用过程中起到及其重要的作用. 目前发展较为成熟的铝钎料主要是 Al-Si 共晶钎料[3,4]，其具有良好的润湿性能和加工性能，且钎焊铝合金接头强度、母材色泽一致性、镀覆性和抗腐蚀性能都极佳，加之价格十分便宜，受到人们的广泛青睐. 1956 年美国上市商品化的药芯焊丝，极大程度上简化了钎焊工艺. 随着铝合金应用范围的逐渐扩大，人们开始考虑在汽车空调、冰箱制冷、散热器等行业的铝管焊接时使用环状自钎剂钎料的可行性.

文中对现阶段在铝管焊接所需环状 AlSi 自钎剂钎料主要采用挤压—切环或挤压—拉丝—制环等生产工艺中存在的产品活性低、生产周期长、生产效率低等问题，采用热压烧结的方式一次成形自钎剂铝焊环，在大大简化铝焊环制造工艺的基础上，提高了生产效率和灵活性.

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1 试验方法

试验采用 40 目的 Al88Si 粉状钎料和 200 目的 Nocolok 钎剂(主要成分为 $KAlF_4$). 首先将钎料和钎剂在 100 ℃的烘箱保温 1 h 进行干燥处理，然后将钎剂和钎料按 85∶15 的质量比混合，在 KQM-X4C/B 型行星式四头快速球磨机中混合 3 min. 采用 SMVB60 热压烧结机制备 Al88Si 自钎剂钎料环，试验装置如图 1 所示.

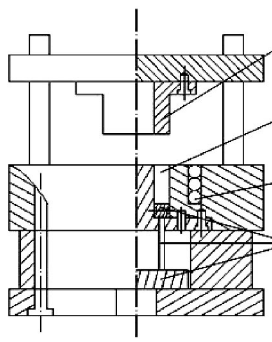


图 1　热压烧结模具示意图
Fig. 1　Schematic diagram of hot pressed sintering mould

采用装粉靴将混合粉末装入模具型腔内，上压头带动凸模往复运动将混合粉压实并排除模具型腔中混合粉内的气体，重复上述操作直到得到厚度为 3.5 mm 钎料环，最后在 54 kN 压力下快速加热到 500 ℃，烧结一定时间，制备出规格为 ϕ18 mm × ϕ13 mm × 3 mm 钎料环.

钎焊母材用 3003 铝合金，试样尺寸为 60 mm ×

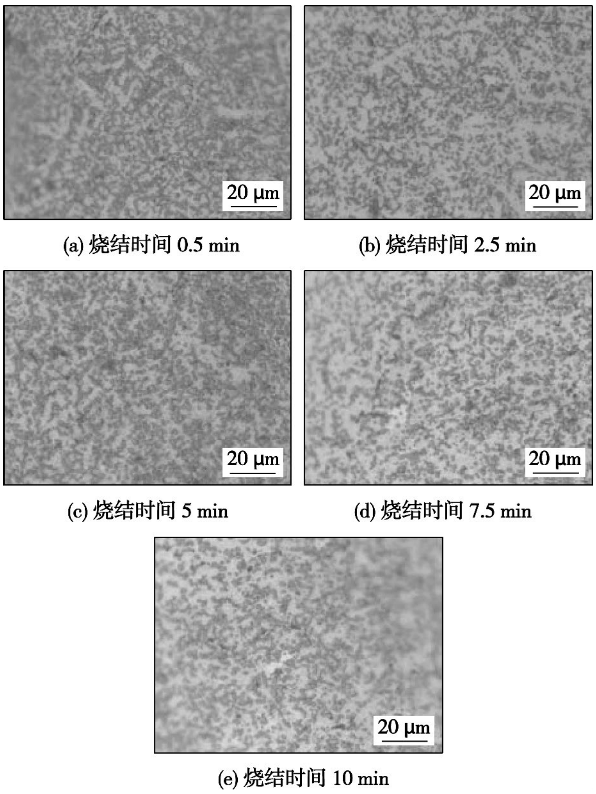
30 mm × 1.5 mm. 钎焊前采用 400 号碳化硅纱布对铝合金表面进行打磨处理，然后用三氯乙烯去除母材表面油污后放入 15% 的 NaOH 溶液中清洗 15 s，清水洗净后再用 15% 的 HNO_3 溶液清洗 10 s 以去除母材表面碱液，清水洗净后再用无水乙醇清洗后自然晾干.

试验时对接接头间隙取 0.2 mm，使用 SP-15 高频感应焊机进行钎焊，钎焊温度 590 ℃，钎焊时间 2 min ± 1 min. 利用 50 kN 液压式万能试验机对钎焊接头的强度进行测试. 采用 Axio Scope. A1 光学显微镜和 JSM-7500F 扫描电子显微镜对钎料显微组织和钎焊接头钎缝组织进行观察.

2 试验结果与分析

2.1 自钎剂钎料的显微组织分析

图 2 为在不同烧结时间条件下制备的 Al88Si 自钎剂钎料的显微组织.



(a) 烧结时间 0.5 min (b) 烧结时间 2.5 min

(c) 烧结时间 5 min (d) 烧结时间 7.5 min

(e) 烧结时间 10 min

图 2 不同烧结时间的自钎剂钎料显微组织

Fig. 2 Microstructure of self-fluxing filler metals with different sintering time

由图 2 中可以看出自钎剂钎料主要由灰白色基体以及分布在上面灰色块状相组成. 随着烧结时间的增加，自钎剂钎料的灰色块状相长大. 为了便于看出钎料显微组织组成，采用扫描电子显微镜观察烧结时间为 2.5 min 的自钎剂钎料显微组织形貌如图 3 所示. 由图 3 中可以看出，灰白色基体为 AlSi，基体表面不仅分布着灰白色块状相，还有白色小颗粒. 由 Al-Si 二元相图可知块状相为初晶硅，而白色小颗粒为 $KAlF_4$ 钎剂.

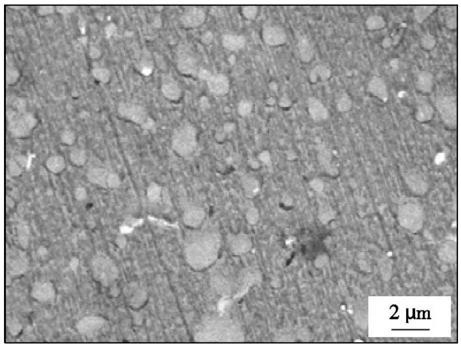


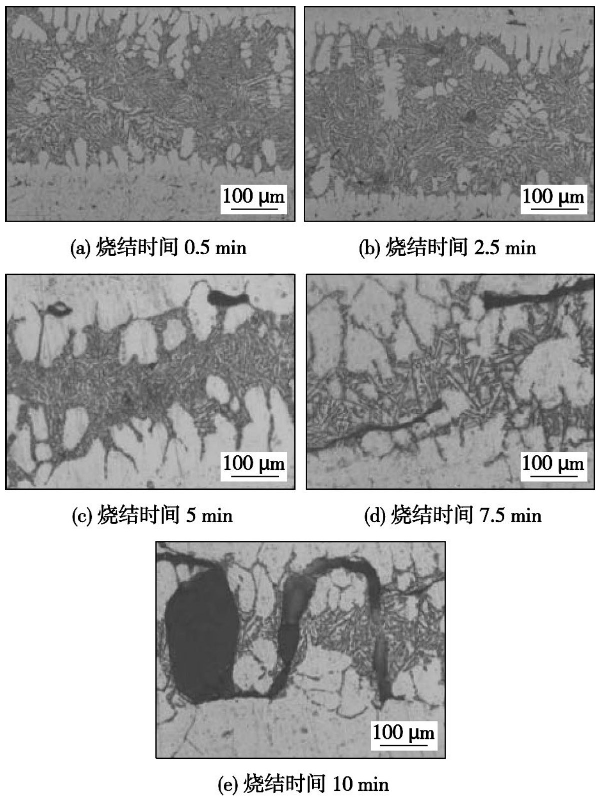
图 3 自钎剂钎料 SEM 图像

Fig. 3 SEM image of the self-fluxing filler metal

2.2 钎焊接头显微组织及 EDS 分析

2.2.1 钎焊接头显微组织

图 4 所示为不同烧结时间的 Al88Si 自钎剂钎料



(a) 烧结时间 0.5 min (b) 烧结时间 2.5 min

(c) 烧结时间 5 min (d) 烧结时间 7.5 min

(e) 烧结时间 10 min

图 4 不同烧结时间自钎剂钎料钎焊接头显微组织

Fig. 4 Microstructure of brazed joint using self-fluxing filler metals with different sintering time

钎焊 3003 铝合金接头钎缝显微组织形貌.

如图 4 中所示，采用 0.5 min 和 2.5 min 烧结时间制备的钎料钎焊接头钎缝均匀饱满，由钎缝中心、界面区和母材组成. 在钎焊接头界面区基本上是由合金元素 Si 向母材铝中扩散后形成的固溶体组织组成. 由于合金元素 Si 的扩散导致钎缝近界面区的组织与钎料原始组织不同，但钎缝中心还存在着少量块状初晶硅相.

由图 4 中可以看出随着烧结时间的增长，钎料的流铺性能大大降低，钎焊接头中裂纹、固体夹杂、未钎满、孔穴等缺陷增多. 这是由于随着烧结时间的增长，钎料中 $KAlF_4$ 钎剂含量减少导致钎料活性降低. 如图 5 所示，烧结时间在 0.5 min 时钎料中白色钎剂小颗粒均匀分布在基体上，烧结时间在 5 min 时钎剂小颗粒数量明显减少，基本不存在大颗粒状钎剂，而烧结时间达到 10 min 后，钎料基体上只存在少量钎剂小颗粒.

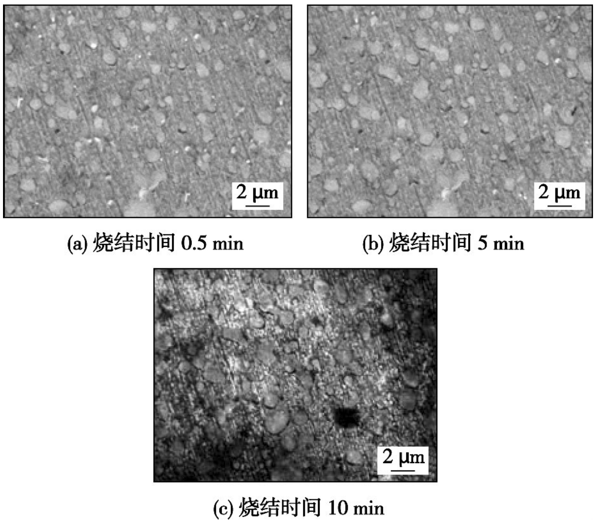


图 5　不同烧结时间钎料中钎剂含量

Fig. 5　Content of flux in filler metals with different sintering time

$KAlF_4$ 钎剂热稳定性差，在空气中烧结时会发生化学反应[5]. 但氧化反应主要在干燥空气或氧气中发生，且 800 ℃以上才明显的察觉，所以氧化反应不是主要影响因素.

2.2.2　钎焊接头 EDS 分析

2.5 min 烧结时间制备的自钎剂钎料钎焊 3003 铝合金钎焊接头钎缝 SEM 图像如图 6 所示. 图 6 中特征点 A，B 成分分析结果如表 1 所示. 由图 6 中可以看出，钎缝组织由灰白色基体和银白色针状组织组成. 结合 EDS 结果分析可知，灰白色基体为 Al_α 固溶体，银白色针状组织为共晶硅相.

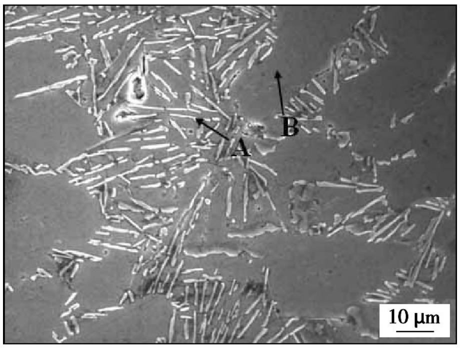


图 6　烧结时间 2.5 min 的钎焊接头 SEM 图像

Fig. 6　SEM image of brazed joint using filler metal with 2.5 min sintering time

表 1　钎缝化学成分分析结果(质量分数，%)

Table 1　Results of chemical compositions in brazing seam

位置	Al	Si
A	49.07	50.93
B	98.63	1.37

2.3　力学性能

不同烧结时间 Al88Si 自钎剂钎料钎焊 3003 铝合金接头抗拉强度如图 7 所示. 由图 7 中可以看出，烧结时间 2.5 min 以上的钎料，钎焊接头抗拉强度下降. 这是由于随着烧结时间的增长，钎料铺展性能下降，直接导致钎焊接头中裂纹、固体夹杂、未钎满、孔穴等缺陷(图 4)的增加. 由图 7 还可以看出，钎料烧结时间为 0.5 min 和 2.5 min 时，钎焊接头抗拉强度在 60 MPa 左右，基本上能满足防锈铝、纯铝等铝合金工件的使用性能要求.

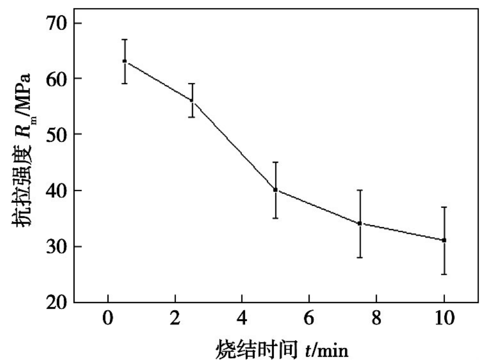


图 7　不同烧结时间钎料钎焊接头抗拉强度

Fig. 7　Tensile strength of brazed joints using self-fluxing filler metals with different sintering time

3　讨　论

热压烧结制备自钎剂钎料时，烧结时间对

Al88Si 钎料的润湿性能影响很大，主要是因为 $KAlF_4$ 钎剂热稳定性差，烧结时间增长使得钎料中钎剂含量逐渐减少. 热压烧结制备钎料时，烧结时间控制在 2.5 min 以内最佳.

Al88Si 钎料的熔化温度(577 ℃)偏高，仅适用于钎焊防锈铝、纯铝等少量牌号的铝合金. 开发以 AlSi 系钎料为基础的低熔点高强度钎料作为铝合金钎焊材料发展的热点已取得一些列成果[6-13]. 只要通过改进或开发出匹配的无腐蚀性钎剂，低熔点 Al-Si 系钎料可用此方法热压烧结成所需规格自钎剂钎料环，从而满足不同牌号的铝管件的连接.

4 结 论

(1) 钎料组织由 AlSi 基体、块状初晶硅和 $KAlF_4$ 小颗粒组成. 随着烧结时间的增加，块状初晶硅长大.

(2) 钎焊接头组织由灰白色 Al_α 固溶体以及银白色针状共晶硅组成.

(3) 随着烧结时间的增加，钎剂发生水解反应导致钎料流铺性能降低，钎焊接头中裂纹、固体夹杂、未钎满、孔穴等缺陷增加，接头强度降低.

(4) 此热压烧结法制备 Al88Si 自钎剂钎料环性能可靠，满足铝合金管的焊接要求.

参考文献:

[1] 张士林，任颂赞. 简明铝合金手册 [M]. 上海: 上海科学技术文献出版社，2006.

[2] 龙伟民，乔培新，王海滨，等. 粉末合成钎料的探讨 [J]. 机械工程学报，2001，37(10)：107-108.
Long Weimin, Qiao Peixin, Wang Haibin, *et al*. Discussion of power synthetic filler materials [J]. Chinese Journal of Mechanical Engineering, 2001, 37(10): 107-108.

[3] 熊华平，李 红，毛 唯，等. 国际钎焊技术最新进展 [J]. 焊接学报，2011，32(5)：108-112.
Xiong Huaping, Li Hong, Mao Wei, *et al*. Reviews on latest advances in brazing and soldering technologies [J]. Transactions of the China Welding Institution, 2011, 32(5): 108-112.

[4] 刘相法，费振义，乔进国，等. Al-Si 合金中 Si 相的团粒化研究 [J]. 铸造，2003，52(8)：538-541.
Liu Xiangfa, Fei Zhenyi, Qiao Jinguo, *et al*. Spheroidization of eutectic and primary Si Crystals in hypoeutectic and eutectic Al-Si alloys [J]. Foundry, 2003, 52(8): 538-541.

[5] 张启运，庄鸿寿. 钎焊手册 [M]. 北京: 机械工业出版社，2007.

[6] 邹家生，吕思聪，赵宏权，等. Al-Si-Cu-Zn 急冷钎料钎焊铝及其合金的界面结构及强度 [J]. 焊接学报，2008，29(3)：77-80.
Zou Jiasheng, Lv Sicong, Zhao Hongquan, *et al*. Microstruction and strength of aluminum and aluminum alloy joint brazed with rapidly cooled Al-Si-Cu-Zn filler metals [J]. Transactions of the China Welding Institution, 2008, 29(3): 77-80.

[7] 朱 宏，薛松柏，盛 重. 6063 铝合金阶梯焊中温钎料腐蚀性能 [J]. 焊接学报，2009，30(10)：29-32.
Zhu Hong, Xue Songbai, Sheng Zhong. Corrosion resistance of intermediate temperature filler metal for stepped welding to 6063 aluminum alloy [J]. Transactions of the China Welding Institution, 2009, 30(10): 29-32.

[8] Tsao L C, Weng W P, Cheng M D, *et al*. Brazeability of a 3003 Aluminum alloy with Al-Si-Cu-based filler metals [J]. Journal of Materials Engineering and Performance, 2002, 11(4): 360-364.

[9] Chang S Y, Tsao L C, Li T Y, *et al*. Joining 6061 aluminum alloy with Al-Si-Cu filler metals [J]. Journal of Alloys and Compounds. 2009, 448(1): 174-180.

[10] Humpston G, Sangha S P, Jacobson D M. New filler metals and process for fluxless brazing of aluminium engineering alloys [J]. Materials Science and Techonogy, 1995, 11(11): 1161-1168.

[11] Chuang T H, Tsao L C, Tsai T C, *et al*. Development of a low-melting-point filler metal for brazing aluminum alloys [J]. Metallurgical and Materials Transactions A. 2000, 31(9): 2239-2245.

[12] 薛松柏，董 健，吕晓春，等. LY12 铝合金中温钎焊技术 [J]. 焊接学报，2003，24(3)：21-23.
Xue Songbai, Dong Jian, lv Xiaochun, *et al*. Brazing technology of LY12 Al-alloy at middle temperature [J]. Transactions of the China Welding Institution, 2003, 24(3): 21-23.

[13] 王 冠，李远波，郭忠宁，等. 汽车散热器新型铝合金钎焊接头腐蚀行为的分析 [J]. 焊接学报，2011，32(6)：25-28.
Wang Guan, Li Yuanbo, Guo Zhongning, *et al*. Research on corrosion of automobile condenser brazed with novel aluminum alloy [J]. Transactions of the China Welding Institution, 2011, 32(6): 25-28.

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Key words: Double wire pulsed welding; probability density distribution; welding stability; quantitative evaluation

Electrostatic probe analysis of current-carrying region in constricting TIG arc with insulating sheet

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Abstract: The shape and current density of current-carrying region in constricting TIG arc with insulating sheet were analyzed by the low disturbance electrostatic probe. The floating potential and ion saturation current of probe were obtained separately in sections at different location along arc axial direction. The results show that the insulating sheet is over the arc root to make the arc not be constricted; with the constriction of insulating sheet, the current-carrying region pinches in the direction of constriction and potential gradient increase. When the constriction effect on arc root is intensified, both of the current density and temperature of current-carrying region are enhanced, and the heat is much moreconcentrated near the center of current-carrying region section.

Key words: constricting TIG arc with insulating sheet; electrostatic probe; diagnostic of plasma

Effect of sintering time on microstructure and mechanical properties of self-fluxing filler metal

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Abstract: Al88Si self-fluxing filler metal ring was prepared by hot pressed sintering. Microstructures of self-fluxing filler metal at different sintering time were analyzed. And the microstructure and mechanical properties of brazed joint withself-fluxing filler metal at different sintering time were also studied. It was suggested that microstructure of self-fluxing filler metal is composed of matrix phase AlSi, block primary crystal silicium andgranular$KAlF_4$. The activity of flux decreases with the increase of sintering time. The microstructure of 3003 Al alloy brazed joint is composed of α-Al solid solution and acicularеutectic silicium. The wettability of self-fluxing filler metal gets worse and the amount of the crack, solid inclusion, incompletely filling, and voids increase with the increase of sintering time, which decreased the tensile strength of aluminum alloy joint.

Key words: self-fluxing filler metal; aluminum and aluminum alloy; AlSi filler metal; sintering time

Analysis of motion accuracy reliabilityfor arc welding robot based on ADAMS/View

LI Chang, WANG Bingchen, HA Xing, YU Xiaoguang (School of Mechanical Engineering & Automation, University of Science and Technology Liaoning, Anshan 114051). pp 63 – 66

Abstract: The inner transmission accuracies of the arc welding robots would cause cumulative errors on the motion paths of welding gun, and which inevitably causes low welding quality. Therefore, it was a key problem how to control the transmission accuracies and different random errors of the welding robots in improving the original designqualities of welding robot. A motion accuracy reliability analysis method was introducedfor the arc welding robot with ADAMS/View software. A Monte Carlo parametric virtue prototype of the robot was built and its different error distributions were simulated by the pseudo-random number sub-function program by using multiplicative congruential method, and then a large sample data in the dynamic welding process were obtained. The robot motion reliabilities can be calculated based on these data. It showed that the advantages of this method include simplicity (no need to solve complex dynamic mathematical models), high accuracy, and efficiency.

Key words: arc welding robot; motion reliability; random error analysis; virtual prototype

Deformation behaviors and equivalent model of TIG welded joint of 6063 aluminum alloy

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Abstract: The FEM were founded to simulate the tensile behavior for butt joint of 6063 aluminum alloy by TIG welding basedon the software of ABAQUS. The effects of HAZ width and thickness on deformation of joint were studied. Andthen the equivalent model of aluminum alloy TIG welded joint was established, which was validated by the thin-walled tube with weld seam. The results indicate that the stress states of welded joints with uneven mechanical properties are complicated compared to the base material. There is sudden change of thetriaxial stress between the base material and HAZ and between the weld metal and HAZ. At the same time, the position of the maximum triaxialstress is transferredfrom the boundary between the base material and HAZ to the boundary between the weld metal and HAZ with the increase of the width of HAZ. The triaxialstress of the welded joint depends on both the thickness of specimen and the geometrical dimension of welded joint. The equivalent model of aluminum alloy welded joint is 20mm in width. The fine model and the equivalent model for aluminum alloy thin-walled tube with welding line are in goodagreement.

Key words: aluminum alloy TIG welded joint, deformation, FEM analysis, equivalent model

Tandem automatic welding technology for oil and gas pipelines

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