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强度失配焊接接头的裂纹尖端张开位移数值分析

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摘 要：采用有限元方法对平面应变条件下含裂纹不同强度失配的平板拉伸焊接接头进行了弹塑性分析，研究了焊缝与母材强度失配、裂纹长度、母材应力应变曲线类型等因素对焊接接头裂纹尖端张开位移的影响．结果表明，强度失配系数增大，焊接接头裂纹尖端张开位移值降低，裂纹长度越短，强度失配的影响越显著．母材无屈服平台时，裂纹尖端张开位移随外加应变的增大呈单调上升趋势，母材有屈服平台时，在高匹配或者裂纹长度较短时，裂纹尖端张开位移曲线会出现阶段性变化，这主要是由于母材形变硬化滞后焊缝变形所产生的．

关键词：强度失配；裂纹驱动力；裂纹尖端张开位移；有限元法
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0 序 言

在焊接结构中，接头是承受外载的基本保证，其断裂结构的安全性至关重要．建立在断裂力学基础上的“合于使用”原则的缺陷评定标准兼顾了安全性和经济性，为焊接结构的设计、制造和安全运行提供了有效手段．焊接接头是一个由焊缝、母材、热影响区（HAZ）组成的非均质体，焊缝和母材的力学性能具有明显的差异，其宏观表现为强度失配性．强度失配性影响接头的整体变形和承载能力，也影响焊缝区裂纹扩展驱动力．这必然会导致非均质焊接接头裂纹驱动力与均质体有很大不同．众多研究[1-7]表明，力学失配对焊缝裂纹驱动力的影响与裂纹长度、焊缝尺寸等因素有关，在缺陷评定中忽略这些因素会导致对裂纹驱动力的高估或者低估，影响评定结果的准确性．

将裂纹尖端张开位移（crack tip opening displacement，CTOD）作为断裂参量在焊接结构合于使用评定中得到广泛应用．焊接接头CTOD行为受控于强度失配性，研究强度失配性对焊接接头CTOD行为的影响对于含缺陷焊接结构的评定具有重要意义．文中采用德国GKSS研究中心提出的局部CTOD—δ_5（跨越裂纹尖端5 mm处测得的张开位移）作为裂纹尖端张开位移参量，对平面应变条件下含裂纹的不同组配的焊接接头进行有限元分析，研究了裂纹长度、焊缝与母材强度失配、母材应力应变曲线类型等因素对焊接接头裂纹尖端张开位移的影响．

1 有限元模型

采用平板对接拉伸模型，将模型简化为焊缝和母材两个部分并假设每一部分的力学性能都是均匀的．焊接残余应力是焊接接头固有的特点，其大小和分布与具体焊接方法、参数、焊后热处理方式等有很大关系，而且当存在裂纹时会使残余应力重新分布或释放，在塑性变形较大时影响不大，因此文中不考虑残余应力的影响．模型尺寸为长度 $2L=160$ mm，宽度 $2W=80$ mm，焊缝宽度 $2H=24$ mm，如图1所示．裂纹位于焊缝中心且平行于焊缝与母材的界面，计算中取裂纹长度 $2a$ 为2，8，24 mm和40 mm，相应的裂纹尺寸参量 a/W 分别为0.025，0.1，0.3，0.5．

采用ABAQUS软件进行平面应变条件下弹塑

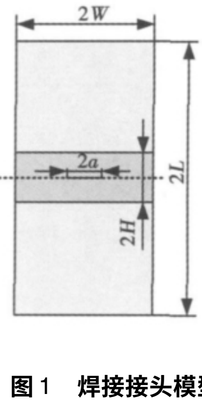

图1 焊接接头模型
Fig. 1 Model of welded joint

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性有限元分析. 由于实际裂纹尖端不可能无限尖锐,所以使用了裂纹尖端半径为 0.005 mm 的钝化裂纹模型. 利用模型对称性,对 1/4 模型进行分析,$a/W=0.3$ 的有限元网格如图 2 所示,共 3 607 个节点、1 146 个单元,单元类型为 8 节点平面应变缩减积分等参单元 CPE8R. 载荷以位移的方式施加,计算中考虑几何非线性的影响.

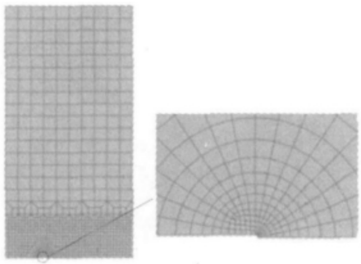

图2 有限元网格($a/W=0.3$)
Fig. 2 Finite element mesh ($a/W=0.3$)

定义焊缝屈服强度与母材屈服强度的比为强度失配系数,用 M 来表示,$M>1$ 称为高匹配,$M<1$ 称为低匹配. 除有屈服平台母材外,其它无屈服平台材料的应力应变曲线均遵循的分段幂硬化规律为

$$\left.\begin{aligned}\varepsilon&=\sigma/E\\ \varepsilon/\varepsilon_Y&=(\sigma/\sigma_Y)^n\end{aligned}\right\}\qquad(1)$$

式中:σ 和 ε 为材料的应力和应变;E 为弹性模量;σ_Y 和 ε_Y 代表材料的屈服应力和屈服应变;n 为硬化指数.

设母材屈服强度为 500 MPa,分为有屈服平台和无屈服平台两种情况,改变焊缝屈服强度,使 $M=0.6,0.8,1.2,1.4$. 计算中输入的有屈服平台母材的真应力应变曲线如图 3 所示.

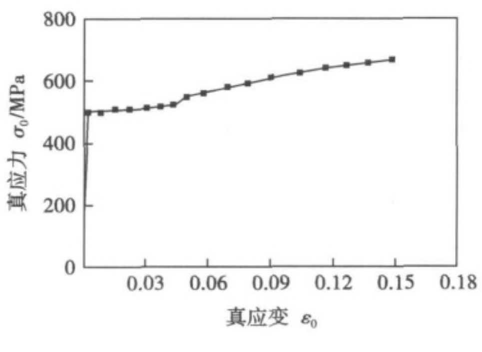

图3 含屈服平台母材的真应力应变曲线
Fig. 3 True stress-strain curve of base material with plateau

2 计算结果分析

图 4 和图 5 分别为母材有屈服平台和无屈服平台时不同裂纹长度的焊接接头在不同强度失配系数

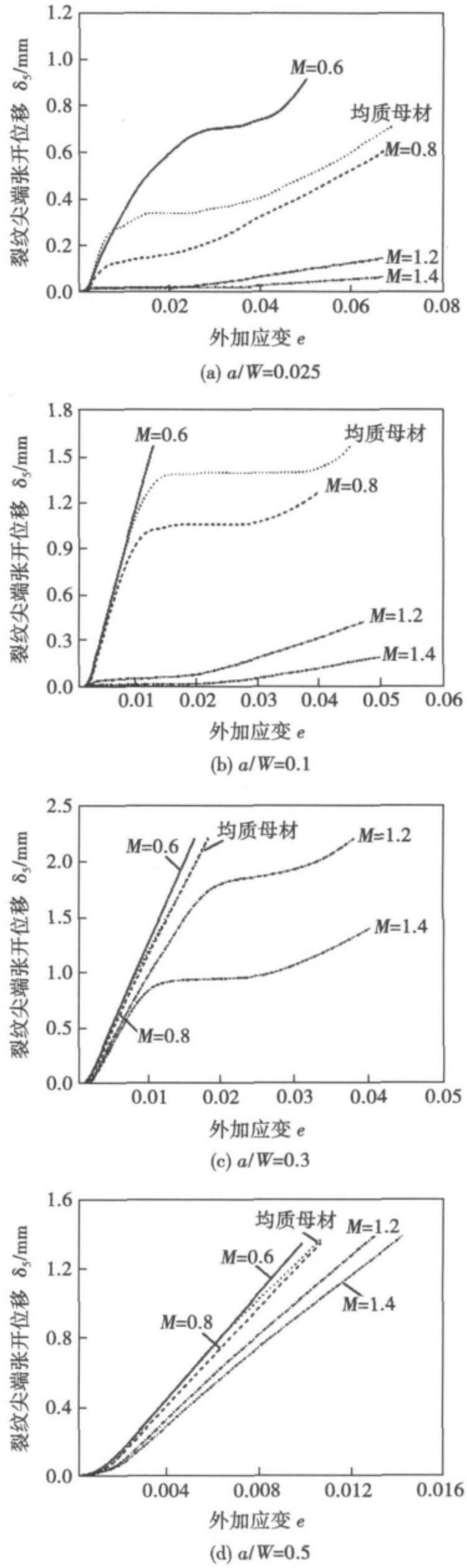

图4 不同失配系数焊接接头的裂纹尖端张开位移与外加应变关系曲线(母材有屈服平台)
Fig. 4 Crack tip opening displacement and applied strain relationship of welded joints (base material with plateau)

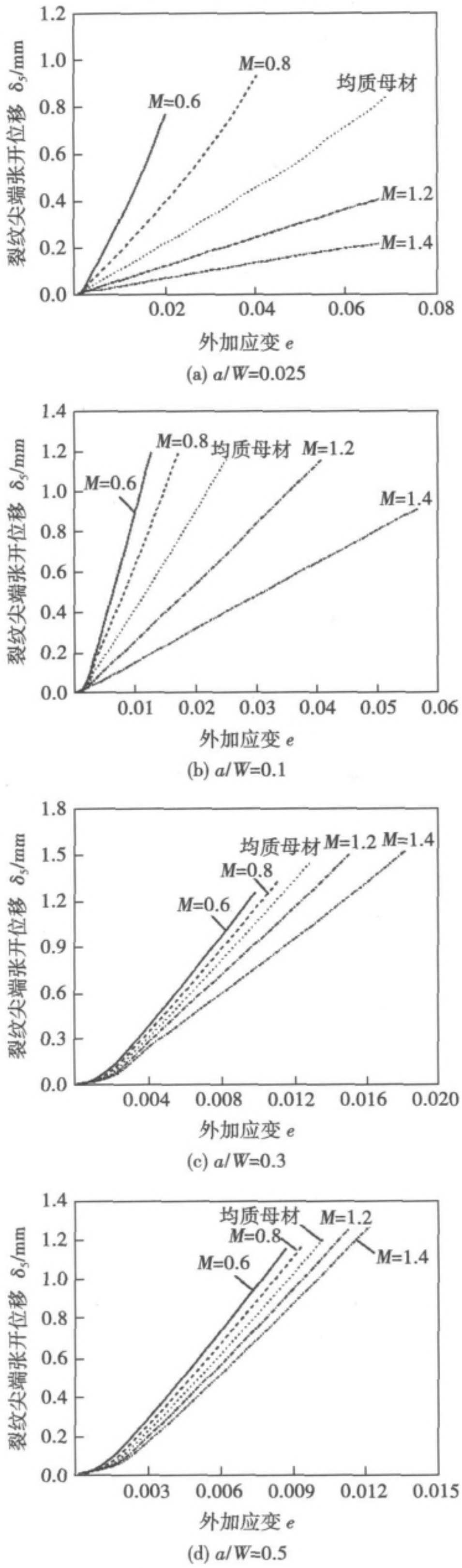

图 5　不同失配系数焊接接头的裂纹尖端张开位移与外加应变关系曲线（母材无屈服平台）

Fig. 5　Crack tip opening displacement and applied strain relationship of welded joints(base material without plateau)

情况时的 δ_5-e 曲线.

需要指出的是，图 4 和图 5 的计算结果是建立在假设材料具有较高延性的基础上的. 从图 4 和图 5 中可以看出，裂纹长度、强度失配系数及母材应力应变曲线形式对接头裂纹尖端张开位移曲线有很大影响. 当外载很小时接头处于整体弹性状态，不同强度失配系数接头的裂纹驱动力 δ_5 相差不大，随着应变的增大，接头进入弹塑性阶段，裂纹尖端张开位移曲线出现较大分离.

对于母材有屈服平台情况，载荷水平一定时，强度失配系数 M 的提高使焊缝裂纹尖端张开位移降低. 图 4 中 $M=0.6$ 的接头裂纹尖端张开位移最大，当外加应变很小时 δ_5 缓慢增长，此后随着外加应变的增大迅速增大，在裂纹非常短（$a/W=0.025$）时 δ_5 会出现一段平台区，δ_5 随外加应变增大保持恒定然后继续上升. $M=0.8$ 接头情况则不同，在裂纹长度较短（$a/W\leqslant 0.1$）时，其接头 δ_5 显著低于均质接头的 δ_5，这是由于尽管焊缝屈服强度低于母材，但是由于母材有较长的屈服平台存在，$M=0.8$ 的低匹配焊缝在硬化后强度超过了母材，变成了实际意义上的高匹配，因此接头 δ_5 低于均质母材；在裂纹长度较长（$a/W=0.3$，$a/W=0.5$）时，$M=0.8$ 接头与均质母材的曲线非常接近，没有显著差异. $M=0.8$ 接头和均质母材在裂纹较短（$a/W\leqslant 0.1$）时 δ_5 曲线也出现了平台区. 对于高匹配接头，δ_5 显著低于均质母材及低匹配接头，当 $a/W\leqslant 0.1$ 时，δ_5 先是随着外加应变缓慢上升，然后出现一段平台区，此后随外加应变增大；$a/W=0.3$ 时 δ_5 先是在外加应变作用下缓慢增大，然后随着应变的增大出现一段快速上升期，此后出现平台区，平台区以后又随外加应变的增大而增大. 当裂纹很长（$a/W=0.5$）时，不同失配接头的 δ_5 曲线随外加应变增大单调上升.

与母材有屈服平台情况不同，母材无屈服平台时，δ_5 曲线随外加应变的增大而增大，呈单调上升趋势. 在裂纹长度一定时，强度失配系数增大，δ_5 降低. 裂纹长度越短，强度失配的影响越显著. 实际上 $a/W=0.025$，$M=1.4$ 的接头 δ_5 曲线存在增长非常缓慢接近平台的一小段区域，这说明无屈服平台材料在裂纹非常短且失配系数非常大的情况下才会出现类似图 4 中的平台形式，图 4 中的大段平台的出现主要是因为母材存在屈服平台，塑性变形由开始的裂纹尖端区域转移到母材中，当母材的形变硬化与焊缝的变形能力同步时，裂纹驱动力才开始继续增加，直到发生全面屈服断裂，而无屈服平台时由于焊缝和母材变形同时进行，因此未出现平台现象.

母材有无屈服平台对于 δ_5-e 曲线的形状影响很

大,母材有屈服平台时,在裂纹较短或失配系数较大的情况下接头曲线出现平台; δ_5-e 关系曲线出现平台反映了裂纹尖端局部变形的“间歇”行为,即裂纹尖端局部变形经过两个阶段,在两个阶段过渡区会出现 $d\delta_5/de \to 0$ 的现象,这与有关试验结果[8,9]是一致的. 而母材无屈服平台时,不同匹配接头的 δ_5 曲线则不会出现平台,裂纹尖端局部塑性变形随应变水平提高成比例连续增大,即 $d\delta_5/de > 0$,给定裂纹尺寸,在塑性变形较大阶段基本为常数.

综上分析表明,各种失配条件下焊接接头裂纹尖端张开位移与总应变在弹性阶段的关系趋于一致,即失配效应不明显. 在弹塑性阶段,δ_5-e 关系变化趋势与失配系数、裂纹长度、母材应力应变曲线形式等因素有关.

3 结 论

(1) 裂纹长度和强度失配系数对焊接接头裂纹尖端张开位移有很大影响. 裂纹长度一定时,强度失配系数增大,焊接接头裂纹尖端张开位移值降低,裂纹长度越短,强度失配对 δ_5-e 曲线的影响越显著.

(2) 强度失配焊接接头的裂纹尖端张开位移与母材应力应变曲线形状有关. 母材无屈服平台时,裂纹尖端张开位移随外加应变的增大呈单调上升趋势. 母材有屈服平台时,在高匹配或者裂纹长度较短时,裂纹尖端张开位移曲线会出现阶段性变化,这主要是由于母材形变硬化滞后焊缝变形所产生的.

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number of needle-like and thread-like tin whiskers were formed on the surface of the oxidized RE phases. It was noteworthy to mention that these tin whiskers kept the constant cross section during growth process. However, besides these regular tin whiskers, some new ones with special morphology, such as lapped whiskers, branch and combination of whiskers, were also found.

Key words: rare earth phase; aging; tin whisker; morphology

Fracture toughness of square drill pipe joint by narrow gap welding MA Caixia[1], ZHANG Se[2], HUANG Xusheng[2], LIN Chengxiao[1], MA Fubao[2], YANG Siqian[1] (1. Shanxi Key Laboratory of Friction Welding Technologies, Northwestern Polytechnical University, Xi'an 710072, China; 2. Shanxi Northfenglei Industrial Group Co., Ltd., Houma 043013, China). pp 77 – 80

Abstract: The test and calculation methods for the dynamic fracture toughness of 40CrMnMo square drill pipe joint produced by narrow gap pulsed metal arc welding were studied. Combined with the use of square drill pipe, pipe size and welding characteristics, the repeated impact 3-point bending test was used to test the fracture toughness of the square drill pipe joint. The crack depth was measured by using a microscope. and K_{Id} values were calculated with a FORTRAN program. The experimental results show that K_{Id} of the weld is 96% of that of the base material, but K_{Id} of the fusion line is only 89% of that of the base material. The analyses on the fracture surface and cross-sectional microstructure indicate that the bulky Widmanstatten structure near the fusion line is the main reason for a lower K_{Id}.

Key words: square drill pipe; narrow gap pulsed gas shielded metal arc welding; fracture toughness

Laser tailor welding of aluminum alloy sheet and cup axon formability of TWB LI Yuntao[1,2], ZHANG Wenjun[1], YANG Lijun[3], ZHANG Jian[1,2] (1. School of Materials Science Engineering, Tianjin University of Technology, Tianjin 300384, China; 2. Tianjin Key Laboratory for Photoelectric Materials Devices, Tianjin 300384, China; 3. School of Materials Science Engineering, Tianjin University, Tianjin 300072, China). pp 81 – 84

Abstract: The process and forming performance of laser tailor-welded board (TWB) of 6061 aluminum alloy were studied. The forming characteristics of TWB in the cup axon trials and the influence of welded beam on overall plastic forming of tailor-welded plate were analyzed. The cupping test results of laser TWB shows that the cracking generally appears in the narrow HAZ. The cupping index of TWB was slightly lower than that of base metal. During the numerical simulation process of cupping test with DYNAFORM software, only the location of the welded beam was considered but its type was ignored, and the results showed that the simulation cracking of the TWB easily occurred at the welded seam below the cupping head with the influence of the welded seam, and the simulation results were slightly different from the practical tests, which was possibly related to the set of the welded seam.

Key words: 6061 aluminum alloy sheet; laser tailor-welded; cup axon formability; DYNAFORM simulation

Establishment of cold cracking susceptibility criterion for X80 pipeline steel LI Yajuan[1,2], JIA Peng[1], LI Wushen[2], XIE Qi[2] (1. College of Science, Civil Aviation University of China, Tianjin 300300, China; 2. School of Materials Science and Engineering, Tianjin University, Tianjin 300072, China). pp 85 – 88

Abstract: The influence of welding heat input, preheat temperature and the deposited metal diffusible hydrogen content were considered, the HAZ critical stress of X80 pipeline steel was tested by implant test based on the orthogonal regression design. The significant factors on the critical stress were obtained by analysis of variance. By multiple linear regression, the critical stress equation and the cold cracking susceptibility criterion were established. The critical stress equation was analyzed. It was concluded that the initial diffusing hydrogen content had great influence on cold cracking susceptibility of X80 pipeline steel. When the initial diffusing hydrogen content is lower, the microstructure is found to be the most important factor on the critical stress. When the initial diffusing hydrogen content is higher, the residual hydrogen content has great influence on the critical stress as well as the microstructure.

Key words: pipeline steel; critical stress; cold cracking; range analysis

Study of microstructure and properties in weld metal of TP304 steel under three processes LI Haitao, YANG Wenjie, WANG Jun, YIN Ke (School of Materials Science and Engineering, Jiamusi University, Jiamusi 154007, China). pp 89 – 92

Abstract: Using three different welding processes, the appropriate welding process parameters were selected and three groups welded joints of TP304 stainless steel were prepared successfully. The microstructure and properties in weld metal zone of TP304 stainless steel under different welding methods were studied by X-fluorescent chemical composition analysis, microstructure observations and micro-hardness test. The results show that alloy composition of weld metal are different and distribute uniformly with different welding methods, microstructure morphology and grain size of the solder layer are quite different. Hardness of the joint is not evenly distribute, weld metal is higher than HAZ, and HAZ is higher than the base metal. Hardness of the weld under TIG-MAG process is maximum and TIG-SMAW process is minimum by comparing three methods. TIG-MAG welding method is better for the thin stainless steel.

Key words: TP304 steel; welding procedure; weld metal; X-ray fluorescence; micro hardness

Numerical analysis on crack tip opening displacement of strength mismatched welded joint XIONG Linyu, ZHANG Yanhua (School of Mechanical Engineering and Automation, Beihang University, Beijing 100191, China). pp 93 – 96

Abstract: Elastic-plastic behaviors of strength mismatched welded joints with cracks were investigated with finite element method. Effects of strength mismatching, crack length and stress-strain curve form of base metal on crack tip opening displacement were analyzed. The results show that the crack driving force increases with the increasing of strength mismatch factor, the influence of strength mismatching for welded joints with shallow cracks is more significant than those with deep cracks. When the base metal doesn't show yield platform, the cracking driving force increases monotonously with the applied strain. For the base metal with yield platform, the cracking driving force and applied strain relationship presents a stage change for over-matched or welded joint with shallow crack, which caused by that the strain hardening of base metal lags behind the deformation of weld metal.

Key words: strength mismatch; crack driving force; crack tip opening displacement; finite element method

Investigation on microstructure and microhardness of linear friction welded joints of dissimilar titanium alloys

ZHANG Chuanchen[1], HUANG Jihua[1], ZHANG Tiancang[2], JI Yajuan[2] (1. School of Materials Science and Engineering, University of Science and Technology Beijing, Beijing 100083, China; 2. Beijing Aeronautical Manufacturing Technology Research Institute, Beijing 100024, China). pp 97 – 100

Abstract: On the basis of previous welding experiments, the dissimilar titanium alloys TC4/TC17 were welded by linear friction welding and the interface temperature was measured. The joint microstructure and microhardness was analyzed and tested by optical microscope, scanning electronic microscope and microhardness tester, respectively. The results showed that the interface temperature during welding exceeds 1 200 ℃, above β-transformation temperature. Recrystallization happens in the weld zone in the cooling process after welding, which forms a refined needle-like structure. The recrystallized structure of the mixture zone is equiaxed and even spheroidized. In the TMAZ of TC4, the microstructure consists of the elongated α phase and the broken β phase. In the TC17 TMAZ, the α and β phases was elongated and fined. The microhardness results showed that strain-hardening occured in TC4 TMAZ, while TC17 TMAZ was softened near the weld zone and strain-hardening was obvious near the base metal.

Key words: linear friction welding; titanium alloy; microstructure; recrystallization; microharhness

Microstructure and properties of ESD coating on aluminum alloy

GUO Feng, SU Xunjia, LI Ping, HOU Genliang (The 501 Staff of the Second Artillery Engineering University, Xi'an 710025, China). pp 101 – 104

Abstract: Using silicon bronze electrode, 2A12 aluminum alloy surface was strengthened by electrospark deposition process. The microstructure, element distribution and phase structure of deposited coating were analyzed by scanning electron microscopic, energy-dispersive spectrum and X-ray diffractometer, respectively. Furthermore, the microhardness distribution and wear resistance of deposition coating were studied by microhardness tester and abrasion tester, respectively. The results show that the deposition coating has an average thickness of about 30 μm and forms metallurgical bonding with the substrate. The deposition coating is mainly composed of Cu-Al intermetallic compounds, its microhardness can reach 578 HV. Compared with the 2A12 aluminum alloy substrate, the wearing volume loss of deposition coating is less than one fifth of the substrate. The surface performance of 2A12 aluminum alloy is improved obviously.

Key words: electrospark deposition; aluminum alloy; microhardness; wear resistance

Investigation on Pop-in phenomenon and its causes in CTOD test for weld metal

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Abstract: CTOD tests were carried out for submerged arc weld seam of offshore platform structures based on BS7448 standard, and the Pop-in phenomenon was assessed and CTOD values were calculated. The results show that when Pop-in phenomenon appears, the fracture toughness CTOD (δ_{Pop}) will decrease several to more than ten times than that without considering Pop-in phenomenon. The research shows that Pop-in phenomenon is mainly due to local brittleness in crack tip, which can be caused by the slag inclusion in local zone of crack tip or the precipitation net in the grain boundary appeared in microstructure of local crack tip. In addition, when there were massive FSP (ferrite side plate) and B (bainite) in one seam of multi-pass weld, local brittleness was easily to occur and lead to Pop-in phenomenon if the crack tip just located in the zone of brittle microstructure and its propagation direction was parallel to the growth direction of brittle microstructure.

Key words: crack tip opening displacement; submerged arc welding; Pop-in phenomenon; local brittleness; fracture toughness

Research on welding robot trajectory and motion simulation based on virtual prototype technology

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Abstract: According to the characteristics of it's structure, a simplified model based on kinematics positive direction analysis of welding robot was presented, with the method of Denavit-Hartenber (D-H) matrix, it then solved the mathematical model of the end pose of the welding robot and the description of welding robot's orientation and posture. With the software ADAMS, the motion simulation model of the welding robot was built up, the simulation trajectory of the end of model was obtained, and which was compared with the solution of the mathematical model to verify the accuracy and reliability of the mathematical model. With the simulation analysis of welding robot, the changes of kinematic parameters of the robot's joints were measured and studied, to provide the basis for subsequent design and manufacture of welding robot. It is very meaningful to set the welding position exactly, to ensure the welding quality and to reduce waster.

Key words: welding robot; motion simulation model; degree of freedom; ADAMS; kinematic simulation