

高强韧低碳中锰钢的弯曲疲劳性能

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摘 要: 利用 GPS-100 高频疲劳试验机,研究了高强韧低碳中锰钢的三点弯曲疲劳性能,绘制出 S-N 曲线并分析了疲劳断口特征,探讨了相变诱导塑性(TRIP)效应对试验钢疲劳性能的影响机理. 结果表明:试验钢的条件疲劳极限为 1 006 MPa,疲劳比为 1. 20;试验钢的疲劳裂纹源萌生于试样下表面靠近棱角的位置,疲劳裂纹扩展区存在大量的二次裂纹可有效降低主裂纹的扩展速率,提高试验钢的疲劳强度;瞬断区包含等轴韧窝和拉长的韧窝,是典型的韧性断裂. 疲劳裂纹前沿微小塑性变形区内的残余奥氏体发生 TRIP 效应,吸收大量应变能,钝化裂纹,减缓裂纹的扩展速率,是试验钢疲劳性能优异的主要原因.

关 键 词: 中锰钢;三点弯曲疲劳;疲劳强度;疲劳比;S-N 曲线;TRIP 效应

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Bending Fatigue Property of Low-C Medium-Mn Steel with High Strength and Toughness

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Abstract: The three-point-bending fatigue property of low-C medium-Mn steel was studied by GPS-100 fatigue testing machine, where the S-N curve was plotted and the characteristics of fatigue fracture surface were analyzed. The effect of transformation induced plasticity(TRIP) on fatigue property of the steel was also investigated. The results showed that the fatigue strength of the tested sample was about 1 006 MPa and the fatigue ratio was 1. 20. The fatigue crack was originated from the corners in the lower surface of the sample. There were a large number of secondary cracks in the crack propagation zone, which could reduce the propagation rate effectively and improve fatigue strength of the steel. The fracture type was ductile for the axial dimples and elongated dimples were observed in the transient fracture zone. Furthermore, the excellent fatigue property of this steel was mainly attributed to the TRIP effect of retained austenite in the small plastic deformation zone in front of the fatigue crack, which could absorb a large amount of strain energy, blunt crack and reduce the crack propagation rate.

Key words: medium-Mn steel; three-point-bending fatigue; fatigue strength; fatigue ratio; S-N curve; TRIP effect

随着经济的快速发展,对能源的需要日益迫切.对能源的开采也逐渐由陆地向深海地区转移,因此海洋平台用钢的需求量不断增加.传统的高强度海洋平台用钢采用低 C 低 Mn 的成分设计,复合添加昂贵的 Ni,Cr,Mo,Cu 等合金元素.采用“淬火+回火”工艺,获得以马氏体为主的强化显微组织^[1],但这类传统的调质钢屈强比一般不低于 0.92^[2].为满足海洋平台安全设计的要求,在钢板强韧性优良的前提下,还需要有较低的屈强比.因此,传统高强钢在海洋平台领域的应用受到限制^[1].

Nakada 等^[3]对 9Ni 钢的研究表明,利用残余

奥氏体的 TRIP 效应可提高钢板的强、韧性能,且屈强比可控.但由于 Ni 价格昂贵,9Ni 钢的工业化推广应用受到限制^[3-4].Mn 元素对钢的相变行为和奥氏体稳定性的影响与 Ni 相似,且价格低廉^[1,5].因此,以 Mn 代 Ni 的成分设计,配合合理的热轧及热处理工艺,可获得残余奥氏体 + 回火马氏体复合层状组织,实现中锰钢高强度、高韧性和低屈强比的良好匹配^[6-7].

现阶段对中锰钢显微组织和力学性能的研究较多^[8],但对其疲劳性能的研究还未见报道.通常,当材料达到 10⁷ 循环周次未断裂,即认为材料具有无限寿命,所对应的最大应力即为材料的高周疲劳极限.疲劳失效是钢结构最为严重的断裂方式之一,研究中锰钢的疲劳性能对中锰钢的工业化推广应用具有重要指导意义.本文通过对中锰钢的三点弯曲疲劳试验,建立了试验钢的 S - N 曲线,确定了其条件疲劳极限,揭示了 TRIP 效应对疲劳性能的影响机理.

1 试验材料与方法

试验钢为鞍山钢铁公司生产的高强韧低碳中锰中厚板,其控轧控冷工艺参数为:开轧温度 1 050 ℃,待温厚度 60 mm,二次开轧温度 900 ℃,终轧温度 850 ℃,终轧后水冷至室温,返红温度 180 ℃.淬火态的中锰中厚板加热至 630 ℃,回火保温 30 min,缓冷至室温.其主要化学成分(质量分数,%):0.05 C,0.2 Si,5.0 Mn,0.008 P,0.006 S,0.40 Cr,0.31 Ni,0.16 Mo.低 C 的成分设计,可有效改善中锰钢的可焊性;Cr 的添加可提高中锰钢的强度和耐腐蚀性;Mo 可有效降低马氏体的回火脆性,提高试验钢的低温冲击韧性.试验钢的力学性能见表 1.

表 1 试验钢的力学性能				
Table 1 Mechanical properties of the tested steel				
屈服强度 MPa	抗拉强度 MPa	断后伸长率 %	屈强比	-20 ℃冲击 功/J
723	835	26.34	0.87	166

沿中锰中厚板的轧向切取三点弯曲疲劳试样,试样尺寸为 10 mm × 10 mm × 75 mm.由于疲劳试验对试样表面光洁度要求较高,在切削加工过程中,需要控制切削速度.在离最终尺寸 0.1 mm 时,需要对试样表面进行磨削,消除试样

表面在加工过程中产生的残余应力.疲劳试样磨削完成后,将试样的工作部分抛光,进行最后的表面处理.

三点弯曲疲劳试验在 GPS - 100 高频疲劳试验机上进行,疲劳试验机的跨距为 60 mm,应力比 $R(\sigma_{\min}/\sigma_{\max})$ 为 0.1,工作频率 90 Hz,试验温度为室温.循环应力振幅为常规正弦波,其中试验载荷由式(1)确定.

$$\sigma = \frac{3PL}{2BH^2} \tag{1}$$

式中: σ 为试样表面的最大应力,MPa; P 为载荷,N;跨距 $L = 60$ mm;试样宽度 $B = 10$ mm;试样高度 $H = 10$ mm.

通常把材料的疲劳应力与疲劳寿命之间的关系曲线称为疲劳曲线,即 S - N 曲线.根据 GB/T 3075 - 2008,采用升降法^[9-10]求中锰钢的疲劳极限,有效试样 13 根.应力增量 $\Delta\sigma$ 一般在预计疲劳极限的 3% ~ 5%,试验在 3 ~ 5 级应力水平下进行到试样断裂或 10⁷ 次时为止.试验钢三点弯曲疲劳极限:

$$\sigma_{0.1\text{弯曲}} = \frac{1}{m} \sum_{i=1}^n v_i \sigma_i \tag{2}$$

式中:有效试验次数 $m = 13$;试验应力水平数 $n = 4$; σ_i 为第 i 级应力水平(MPa); v_i 为第 i 级应力水平下的试验次数($i = 1, 2, \dots, n$).

采用 OLYMPUS 光学显微镜和带有电子背散射(EBSD)的 Zeiss Ultra 55 扫描电镜观察中锰钢金相试样的显微组织形貌.在断裂的疲劳试样上取样,利用 FEI Quanta 600SEM 观察疲劳断口形貌.在疲劳断口表面切取 500 μm 厚的薄片,研磨至 50 μm 后,冲孔成直径 3 mm 的 TEM 试样,电解双喷后,观察疲劳断口处的精细形貌.

2 试验结果

2.1 试验钢的显微组织

试验钢的显微组织如图 1 所示,结合前期研究结果^[4,6-7],试验钢的金相图片和 TEM 精细形貌表明其显微组织由回火马氏体和长条状残余奥氏体组成,残余奥氏体质量分数约为 20%.回火马氏体板条中的位错密度较低,回火马氏体板条和逆转变奥氏体板条宽度分别为 100 ~ 500 nm 和 50 ~ 150 nm.

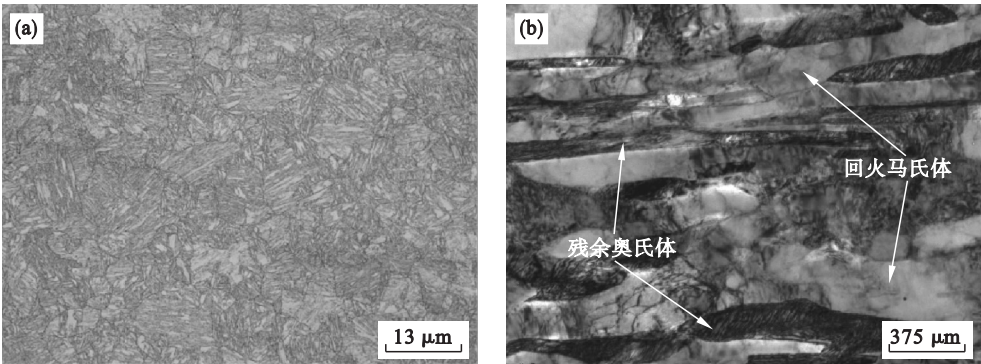


图 1 试验钢 1/4 厚度处的显微组织
Fig. 1 Microstructure of the tested steel at 1/4 thickness
(a)—OM; (b)—TEM.

2.2 试验钢的 S - N 曲线

图 2 为试验钢在应力比 0.1 下的三点弯曲疲劳试验 S - N 曲线. 在高于条件疲劳极限的最大应力值 σ_{\max} 与循环次数 N 满足关系:

$$\sigma_{\max} = A + B \times \lg N . \tag{3}$$

经回归计算确定系数 $A = 1\,418.49$, $B = -59.08$. 根据式(2)求出试验钢的三点弯曲疲劳极限 $\sigma_{0.1\text{弯曲}} = 1\,006\text{ MPa}$. 试验钢的疲劳比 $\sigma_{0.1\text{弯曲}}/\sigma_m = 1.20$, 远高于同强度级别的其他钢种^[11], 即试验钢疲劳性能优异.

2.3 疲劳断口形貌

试验钢的典型疲劳断口形貌如图 3 所示. 图 3a 为宏观疲劳断口形貌, 其中 I 为疲劳裂纹源, II 为疲劳裂纹扩展区, III 为瞬断区. 试样疲劳裂纹

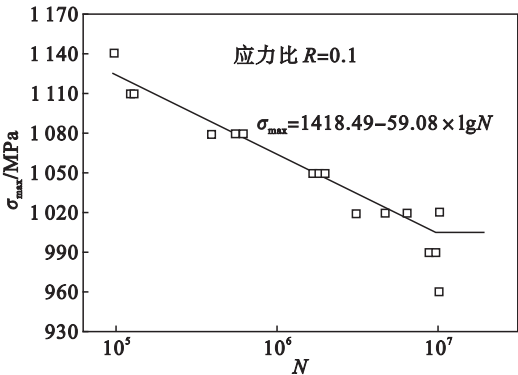


图 2 三点弯曲疲劳 S - N 曲线
Fig. 2 S-N curve of by three-point-bending fatigue test
源萌生于试样下表面靠近棱角的位置, 瞬断区的面积较大, 约占整个疲劳断口的 60%, 表明试验钢塑性较好^[4, 6]. 图3b为疲劳裂纹扩展区中的二

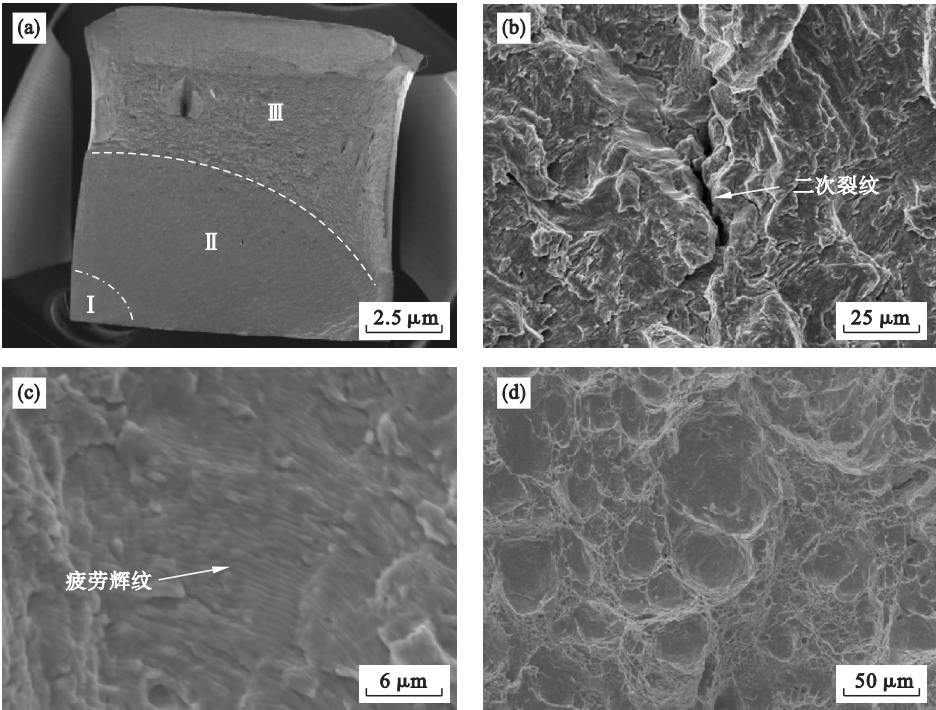


图 3 试验钢的疲劳断口形貌
Fig. 3 Fatigue fracture surface of the tested steel
(a)—宏观形貌; (b)—疲劳裂纹扩展区的二次裂纹; (c)—疲劳裂纹扩展区的疲劳辉纹; (d)—瞬断区.

次裂纹,不断向前扩展的主裂纹遇到塞积的位错,产生应力集中,从而引伸出与主裂纹呈 45° 的二次裂纹^[12]. 二次裂纹的形成和扩展需要消耗大量能量,松弛了应力集中,主裂纹尖端的应力峰值将被大幅度削弱,裂纹的扩展驱动力减小,因此减缓了主裂纹扩展速率,有利于提高试验钢的疲劳强度^[13]. 图 3c 为疲劳裂纹扩展区中的疲劳辉纹,疲劳辉纹是一系列相互平行的条纹,疲劳辉纹的方向垂直于该区疲劳裂纹的扩展方向. 疲劳辉纹是主裂纹在扩展过程中每次循环载荷留下的微观痕迹,是疲劳裂纹扩展区最典型微观特征. 图 3d 为疲劳断口的瞬断区形貌,与冲击断口的纤维区形貌类似,包括等轴韧窝和拉长的韧窝,是典型的韧性断裂.

3 分析讨论

试验钢的晶粒取向分布如图 4 所示,红线代表 2° ~ 15° 的小角度晶界,蓝线代表 ≥ 15° 的大角度晶界. 由图 4 可知,试验钢的回火马氏体板条束中的大角度晶界含量较多.

在高强钢中,裂纹的扩展速率主要取决于大角度晶界的含量^[4]. 大角度晶界能有效偏转甚至终止裂纹的扩展,而小角度晶界对阻碍裂纹扩展的作用较小^[14]. 当试验钢中大角度晶界含量较多时,增加了裂纹转折的次数,使单元裂纹扩展路径减小,总路径增长,从而可以消耗较多的能量,增大裂纹扩展的阻力^[12],可有效提高试验钢的疲劳强度.

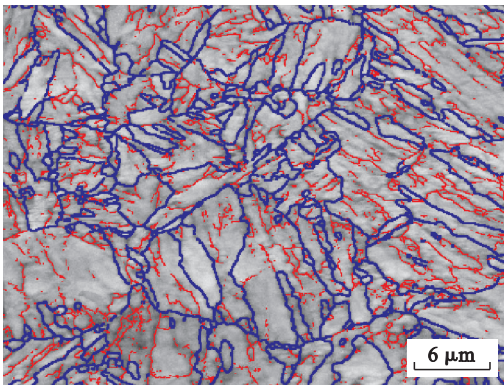


图 4 试验钢的晶粒取向分布

Fig. 4 Grain boundary orientation distribution of the tested steel

图 5 为试验钢疲劳断口处的 TEM 精细形貌,位错墙和析出的碳化物清晰可见. 这是由于,在疲劳循环应力作用下,微小的塑性变形作用在基体上时,晶体中处于软取向部分会优先开动滑移系,

位错不断增殖,发生滑移和攀移,从而形成位错墙. 在疲劳裂纹扩展过程中,裂纹前沿微小塑性变形区内的残余奥氏体将诱发 TRIP 效应,转变为马氏体^[15]. 马氏体相变过程中将会吸收大量的应变能,主裂纹尖端的应力集中被释放,使裂纹尖端变钝. 在发生马氏体相变的同时,体积也会发生膨胀,将对裂纹尖端产生一定的压应力,阻碍裂纹的扩展,大幅度地降低主裂纹的扩展速率^[16]. 此外,在回火过程中及残余奥氏体转变为马氏体的同时,析出了细小弥散的碳化物颗粒,引起的沉淀强化对位错的运动起着阻碍作用,从而降低裂纹扩展速率,提高了试验钢的疲劳强度^[13].

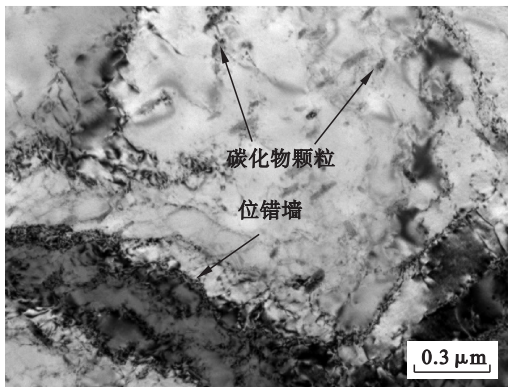


图 5 疲劳断口的 TEM 显微照片

Fig. 5 TEM micrograph of fatigue fracture surface

4 结 论

1) 在应力比 $R = 0.1$ 和循环基数为 10^7 条件下,建立了中锰钢三点弯曲疲劳试验的 S - N 曲线,试验钢的三点弯曲疲劳极限 $\sigma_{0.1\text{弯曲}} = 1\,006\text{ MPa}$,疲劳比 $\sigma_{0.1\text{弯曲}}/\sigma_m = 1.20$,高于条件疲劳极限的最大应力值 σ_{\max} 与循环次数 N 的关系为 $\sigma_{\max} = 1\,418.49 - 59.08 \times \lg N$.

2) 试验钢的疲劳裂纹源萌生于试样下表面靠近棱角的位置,疲劳裂纹扩展区存在大量的疲劳辉纹和二次裂纹,二次裂纹可有效降低主裂纹的扩展速率,提高试验钢的疲劳强度;瞬断区面积约占整个疲劳断口的 60%,包含等轴韧窝和拉长的韧窝,是典型的韧性断裂.

3) 中锰钢高含量的大角度晶界可有效阻碍疲劳裂纹的扩展,降低裂纹的扩展速率;在疲劳裂纹扩展过程中,裂纹前沿微小塑性变形区内的残余奥氏体发生 TRIP 效应,吸收大量应变能,钝化裂纹,减缓裂纹的扩展速率,是试验钢抗疲劳性能优异的主要原因.

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