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Influence of Carbon Equivalent Value on the Weld Bead Bending Properties of High-Strength Low-Alloy Steel Plates

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The contribution of chemical compositions in terms of carbon equivalent value (CEV) on impending crack propagation during weld bead bend tests (WBBTs) was studied with five different high-strength low-alloy steel plates that underwent different rolling processes. The test showed that cracks developed at the weld joint, easily passed through the coarse-grain heat-affected zone (CGHAZ), and finally were arrested within the heat-affected zone (HAZ). An apparent decrease in the average crack length, which consequently indicated improvement in crack arrestability, was found with decreasing CEV. In addition, the relatively fine microstructure in the HAZ of low-CEV steel plates helped in preventing the crack from further propagation. Special emphasis was placed on the empirical expectation of critical CEV above which WBBT might fail.

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1. Introduction

Recently, significant effort has been devoted to increase the capacity of renewable energy resources, such as wind energy industry^[1]. Because steel towers are currently the dominant supporting structures for wind turbines, a great demand exists for large supporting towers, and their optimum design must consist of thick and strong steels of higher grades^[2,3]. Joint requirements for tower construction are also affected by the large size of towers. The larger the wind towers are, the more expensive is the cost for tower construction and also joining between the fan-shaped tower segments, which are generally cut from rectangular parent steel plates. This condition means that the working processes of the weld seams and their quality assurance become more important in spite of the expensive and time-consuming tasks^[4].

The life cycle of a wind turbine tower strongly depends on both the grade of the parent steel plates and their joint properties under the same geometrical design. In general, stress- or fatigue-induced failures locally originate from the more stressed zones of a component, which might be the point of geometrical or material

heterogeneity^[5]. The welded joint between cans or tubular nodes in a tripod, typically made by shielded metal arc welding (SMAW), could be an example of the aforementioned point. Because the demand for wind turbine towers is strongly affected by flexural loading, understanding the mechanism of crack initiation and propagation under bending or flexural conditions is a prerequisite^[6,7]. Therefore, weld bead bend tests (WBBTs) of steel towers, whose thicknesses are more than 50 mm, are required to assess the ductility and soundness of the welded joints by several European countries such as Denmark and Germany, known as mature wind energy markets^[8]. The AUBI (Aufschweißbiegeversuch) test has been considered as the most appropriate guideline of WBBT for thick plates according to SEP1390^[9], which verifies whether a fissure in the weld metal deposit is observed in the heat-affected zone (HAZ) or the underlying material when a tensile load is quickly applied to the welding bead. A long-standing agreement exists that the joint microstructure and strength of the thick steel plate play an important role in the fracture processes responsible for HAZ or weld metal cracking^[10]. However, to the best of our knowledge, no systematic study was conducted on the effect of chemical composition and fabrication process of steel plates on the welding microstructure and subsequent weld bead bending properties. Sedlacek et al.^[9] and Stranghöner^[11] only investigated the influence of plate thickness, bending angle and temperature on the mechanical bending

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Table 1
Chemical compositions of the steel plates used for welding

Material	Sample name	Process	Chemical composition (wt%)												CEV ^a
			C	Si	Mn	V	Cu	Ni	Al	Nb	P	Ti	S	Fe	
S355NL	CR1	CR ^b	0.15	0.40	1.50	—	0.20	0.15	0.03	0.03	≤0.018	0.015	≤0.005	Bal.	0.42
S355J0	CR2		0.16	0.38	1.43	0.04	—	—	0.03	0.03	≤0.018	0.015	≤0.005		0.41
	CR3		0.15	0.35	1.50	—	—	—	0.03	0.02	≤0.018	0.015	≤0.005		0.40
S355M	TM1	TMCP ^c	0.15	0.35	1.10	—	—	—	0.03	0.02	≤0.018	0.015	≤0.005		0.33
S355ML	TM2		0.08	0.30	1.50	—	—	—	0.03	0.02	≤0.018	0.015	≤0.005		0.33

^a CEV = $C_{eq} = \{C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15\}$.

^b CR: controlled rolling.

^c TMCP: thermo-mechanical controlled-rolling process.

performance of joints for several high-strength low-alloy steel plates by applying AUBI test without microstructural characterization.

In the present work, we employed the weld bead bending properties of several structural high-strength low-alloy steels (European standard structural steels, EN 10025). Because achieving minimum recommendations in the manufacturing industry under bending conditions does not mean that the weld of the thick structural steels might have excellent mechanical properties, the purpose of the experimental study is to identify in detail the relationship among chemical composition, microstructures, and subsequent crack arrestability of SAMWed high-strength low-alloy steels subjected to bending.

2. Experimental

2.1. Materials

The five different material plates used as base metals in this study were high-strength low-alloy S355 steels, whose chemical compositions are given in Table 1. Three controlled-rolling (CR) plates

and two thermo-mechanically controlled-rolling-processed (TMCP) plates were respectively designated as CR1, CR2, CR3, TM1, and TM2, depending on the different chemical compositions and cooling methods, as listed in Table 1. The accumulated reduction in the rolling stage was 80%. The thickness of the finished products was 50 mm. After hot rolling, the CR plates were cooled by air, whereas the TMCP plates were cooled by water from the start cooling temperature (SCT) to the finish cooling temperature (FCT) at a cooling rate of 13 °C/s. The basic parameters of the rolling process are listed in Table 2.

After cutting from the position at the quarter thickness of each plate, the metallographic specimens were ground, mirror polished, and etched in a solution of 5% nital for 20 s. Fig. 1 shows the metallographic structure of the thick metal plates. Three CR-plates, namely, CR1, CR2 and CR3, whose carbon equivalent values (CEVs) were above 0.40, consisted of unambiguous polygonal ferrite and banded pearlite. On the other hand, the microstructure of TM1 and TM2 plates, whose CEVs were 0.33, was mainly composed of fine quasi-polygonal ferrite (QPF) and bainite.

The basic room-temperature mechanical properties of the five different plates were characterized by uniaxial tensile and Charpy V-notch (CVN) impact tests. After preparing a flat dog-bone-shaped tensile specimen (ASTM E8) with a gauge length of 20 mm along the direction transverse to the rolling direction, uniaxial tensile test was conducted using a universal testing machine (model ZWICK-Z1200E) at an initial strain rate of $5 \times 10^{-3} \text{ s}^{-1}$. In addition, the fracture toughness was analyzed in accordance with the standard CVN impact test (ASTM E23) after preparing the specimens, i.e., 55 mm × 10 mm × 10 mm with a V-notch, which was as deep as 2 mm with a 45° angle and a 0.25-mm radius. The test temperatures were fixed at −20 and 0 °C. Fig. 2(a) shows the plate where both the tensile and impact test specimens were cut from. For each steel plate, three tensile and Charpy specimens were prepared and tested.

Table 2
Parameters of rolling processes adopted in this study

Sample name	Process	Final thickness (mm)	Reduction ratio	FRT ^a (°C)	SCT ^b (°C)	FCT ^c (°C)	Cooling rate from SCT to FCT (°C/s)
CR1	CR	50	5	812	—	—	—
CR2				842	—	—	—
CR3				789	—	—	—
TM1	TMCP			796	755	537	13
TM2				839	784	679	13

^a FRT: finishing rolling temperature.

^b SCT: start cooling temperature.

^c FCT: finish cooling temperature.

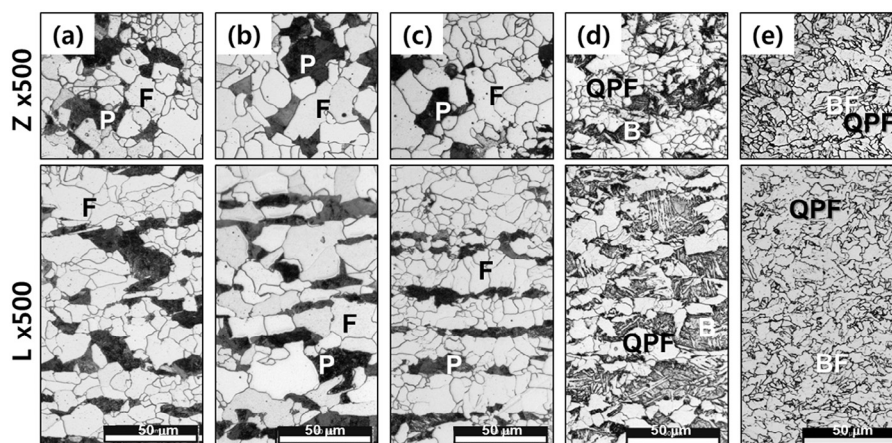


Fig. 1. Representative optical micrographs obtained from (a) CR1, (b) CR2, (c) CR3, (d) TM1 and (e) TM2 steel plates.

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