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EFFECT OF COILING TEMPERATURE ON THE FRACTURE TOUGHNESS OF LOW CARBON STEEL

تأثير درجة حرارة اللف على متانة الكسر للصلب منخفض الكربـــــون

by

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خلاصـــة : كانت الخواص الميكانيكية للصلب المسحوب على البارد وعلى الساخن تحت مختلف ظروف التصنيع موضوعـــا لعدة بحوث، بينما متانة الكسر، وهي خاصية هامة في التصميم لاختيار المواد والاجهادات المناسبة، لم تلق القدر الكافي من الدراسة خاصة بالنسبة لعوامل التصنيع.

وفي هذا البحث، درسنا تأثير درجة الحرارة عند المرحلة النهائية لتصنيع الصلب، أى درجة حرارة اللف، على متانة الكسر للصلب المسحوب والمحتوى على ١ر٠٪ كربون، وقد أخذنا في الاعتبار عوامل أخرى مثل اتجـــاه السحب وسمك ألواح الصلب .

ونظرا لأسباب عملية فان درجة حرارة اللف في الصناعة تكون في حدود ٧١٠ْم ولغرض هذه الدراسة فان ظروف التصنيع قد تم التحكم فيها لتخفيض درجة حرارة اللف الى ٦٢٠ـ٦٣٠ْم.

تشير نتائج البحث الى أن متانة الكسر للصلب منخفض الكربون والمسحوب على البارد وعلى الساخن تتحسن كلما أمكن تخفيض درجة حرارة اللف ، فقد ازدادت متانة الكسر من ١ر١٧٪ الى ١ر٢٥٪ عندما خفضت درجة حرارة اللف من ٧١٠ْم الى ٦٢٠ـ٦٣٠ْم. وعند اجراء الاختبار المجهرى للعينات اتضح أن حجـــم الحبيبات يقل بتخفيض درجة حرارة اللف وينتج عن ذلك تقليل الميل لتوليد شروخ عند حدود الحبيبات مما يؤدى الى زيادة مقاومة المادة للكسر .

1. ABSTRACT

The mechanical properties of hot-and cold-rolled steels under various manufacturin conditions have been the subject of several investigations. Fracture toughness, an importan design factor for the selection of materials and appropriate design stress levels for fractur resistant structures, did not take much attention in this repect.

In this paper, the effect of the temperature at the final steel manufacturing process coiling temperature, on the plane stress fracture toughness for 0.1% carbon rolled stee was investigated. Other aspects such as specimen rolling direction and thickness of strip have been considered.

Owing to practical reasons, the normal operating coiling temperature is set at 710°C For the purpose of this study, the conditions at the coilers have been controlled to bring the coiling temperature down to 630°C.

Test results indicated that the plane stress fracture toughness for the test material has improved by about 17% when the coiling temperature was brought down from 710°C to 630°C. Microstructural examination indicated that the grain size of the material decreased with decreasing the coiling temperature. This is known to be responsible for reducing the tendency to nucleate cracks at the grain boundaries leading to increasing the material's resistance to fracture.

2. INTRODUCTION

Current demands for rolled steels have greatly increased due to modern developments in the expanding motor car and domestic equipment industries. Most of the mild steels used for the production of these equipment are the rimmed, silicon trace type or aluminum killed steels. The hot rolling schedule for these steels includes sufficiently slow cooling for the transformation to ferrite-pearlite structure to occur. The usual hot strip mill consists of reheating furnaces, scale breakers, roughing mills, finishing mills, ending with spray cooling facilities and coilers. The temperature at the coilers, the coiling temperature. is influenced by such factors as the finishing temperature, the time of contact between water and steel strips, the water pressure, and the thickness of the strips. The mechanical properties of the hot rolled strips of a given steel are known to depend mainly on the temperatures and conditions at each of the steel manufacturing processes. [1,2]

A number of investigations have been performed to study the effect of the above-mentioned factors on the mechanical properties of rolled steel. [1-6] The majority of these investigations are concerned with the soaking and the finishing temperatures, while little concern has been given to the effect of the coiling temperature. Fracture toughness, an important design factor for the selection of materials and appropriate design stress levels for fracture resistant structures, had the least attention in this regard.

The aim of this paper is to perform an experimental study on the effect of changing the coiling temperature on the plane stress fracture toughness of hot-and cold-roled steel sheets.

3. EXPERIMENTAL PROCEDURE

3.1 MATERIALS

Steel slabs having similar nominal chemical composition were hot-rolled following the ordinary reductiom schedule for the purpose of this study. The average soaking temerature was set at 1300 C, while the average temperatures before and after the roughing mills were set at 1200 C and 1050 C, respectively. An average finishing temperature of 870 C was maintained. The slabs were then rolled mainly in the reversing mill using the coil rolling method. It is necessary to have finishing temperatures during the hot-rolling process above the transformation temperature, AC, to ensure uniform and fine grains. [7]

The nominal chemical composition of the low carbon steel used for this investigation is shown in Table (1). The testing slabs were produced by the continous casting plant. The nominal dimensions of each slab were 140 x 1030 x 5800 mm. The slabs were divided into three groups which were hot-rolled to 3.5, 3.0, and 2.5 mm. thickness. The coiling temperature for both the 3.0 and 3.5 mm. thickness groups ranged from 710 C to 630 C with an increment of 20 C. The coiling temperature for the 2.5 mm. thickness group ranged from 700 C to 620 C with an increment of 20 C. Achievement of lower coiling temperatures was possible only for the smaller thickness because of the higher rate of heat transfer which may be obtained in thinner sections. Efforts to decrease the coiling temperature for thicker sections have failed due to the limited efficiency of the cooling system. The hot-rolled specimen were taken from the resulting coils which were then cold-rolled, for the rest of the experiments, to of 1.6, 1.25, and 0.8 mm., resectively. After each rolling process, one batch was taken from the front of the rolled coil and another was taken from the tail in order to obtain representative results through the coils. The batches, from which the test specimens were cut, had the dimensions of 1000 x 3000 mm. For both hot- and cold-rolled batches, a total of (240) specimens were taken in such a way that (120) specimens were cut in the rolling direction and the other (120) were cut normal to the rolling direction. This was done to account for the anisotropy of the material.

3.2 TEST SPECIMENS AND EQUIPMENT

The plane stress fracture toughness, K_c, was determined using double-edge notched specimens with sharpened ends. The standard specimens, shown in Fig. (1), were taken according to ASTM Standard E-399. The average mechanical properties of the test material (0.1% carbon steel) are shown in Table (2).

Table (1) The Nominal Chemical Composition of the Test Material

Hot- Rolled Strip Thickness, mm.	Elements & Percent Weight				
	C	Si	Mn	P	S
2.5	0.1	0.14	0.3	0.035	0.02
3.0	0.1	0.14	0.3	0.04	0.019
3.5	0.1	0.15	0.29	0.04	0.02

Table (2) The Average Mechanical Properties (Tensile) for the Test Material

Yield Stress, σ_y, MPa		Ultimate Stress, σ_u, MPa		% age Elongation	
Hot-Rolled	Cold-Rolled	Hot- Rolled	Cold-Rolled	Hot-Rolled	Cold-Rolled
275	265	400	385	30	33

The specimens were tensile fractured on a Universal Testing Machine Type VEB, WERKSTOFF-PRUFMASCHINEN, LEIPZIG with a maximum loading capacity of 30 tons. The fracture toughness was first calculated using Irwin's formula [8], Eq. (1), and then was corrected by adding the plastic zone size, Eq. (2). to the crack length. [9].

$$K_c = \frac{P_m}{t\sqrt{w}} \left[\tan \frac{\pi a}{w} + 0.1 \sin \frac{2\pi a}{w}\right]^{1/2} \qquad \ldots (1)$$

$$r_p = \frac{1}{2\pi} \left[\frac{k_c}{\sigma_y}\right]^2 \qquad \ldots (2)$$

In Equations (1) and (2), P_m is the maximum fracture load, a is the notch depth to which the plastic zone size will be added, w is the specimen width, and σ_y is yield strength of the material.

4. TEST RESULTS AND DISCUSSION

The experimental results of this test are summarized in Figs. (2) to (5). The variation of the plane stress fracture toughness with coiling temperature and specimen thickness is indicated in Figs. (2) and (3) for hot-rolled steel sheets. Similarly, the variation of the plane stress fracture toughness with coiling temperature and specimen thickness is shown in Figs. (4) and (5) for cold-rolled steel sheets. Investigation of the Figures indicate that the plane stress fracture toughness increases as the coiling temperature decreases. It is also shown that, for a given coiling temperature, the fracture toughness increases as the thickness increases. This seems to be reasonable since the thickness is smaller than the plane strain transition thickness, i. e. $t \ll 2.5\,(K_c/\sigma_y)^2$. The percentage increase in the fracture toughness for hot-rolled steel is found to be 20.3%, 18.3%, and 17.6% for thickness of 3.5, 3.0, 2.5mm., respectively when the coiling temperature decreased by 80 C. For cold-rolled steel, the percentage increase in the fracture toughness is 25.6%, 21.8%, and 20% for thicknesses of 1.6, 1.25, and 0.8 mm., respectively for the same reduction in coiling temperature. To explain the inverse relation between the fracture toughness and coiling temperature of rolled steel sheets, microstructural examination of rolled steel samples were taken at various coiling temperatures. The microstructural tests revealed that higher coiling temperatures result in coarser grain size, as shown in Fig. (6). Coarser grain size increases the number of dislocations contained in the pile-up leading to high stress on the dislocation at the front of the pile-up. This high stress causes cracks to nucleate at the grain boundaries [10] which leads to lowering the resistance of the material to progressive crack extention, i.e. lower fractore toughness. A logical conclusion is the increase in the fracture toughness at finer grain size.

Smith [11] derived a fracture criterion which takes the form:

$$\left(\frac{C_o}{d}\right) \sigma_f^2 + \tau_{eff}^2 \left\{1 + \frac{4}{\pi} \left(\frac{C_o}{d}\right)^{1/2} \frac{\tau_i}{\tau_{eff}}\right\}^2 \geqslant \frac{4e\,\gamma_p}{\pi(1-\nu^2)\,d} \qquad \ldots (3)$$

where C_o = carbide thickness, d = grain diameter, τ_{eff} = effective shear stress, τ_i = friction stress, γ_o = effective surface energy, and σ_f = fracture stress. Investigation of this fracture criterion indicates that the relationship between the grain diameter, d, and the fracture stress, σ_f, and hence, the fracture toughness is an inverse relationship. This would be true when the other factors in the criterion are held invariants, which may be the case for rolled low carbon steel [10].

5. CONCLUSIONS

Test results for 0.1% carbon, hot-and cold-rolled steel show that: the plane stress fracture toughness has improved by 17.6% to 25.6% when the coiling temperature was brought down from 710 C to 630 C. Micro-structural examination indicated that the grain size of the material decreased with decreasing the coiling temperature. This is known to be responsible for reducing the tendency to nucleate cracks at the grain boundaries leading to increasing the material's resistance to fracture.

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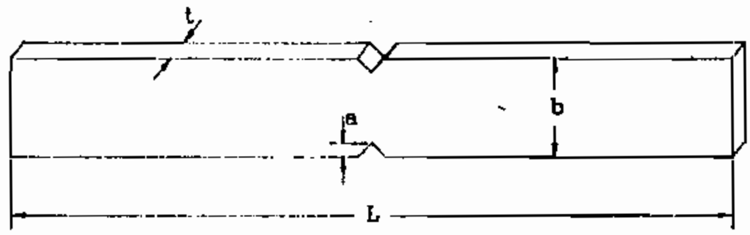

L = 300 mm a = 7 mm
b = 45 mm t = 0.8–3.5 mm

Fig.(1) Plane stress fracture toughness specimen.

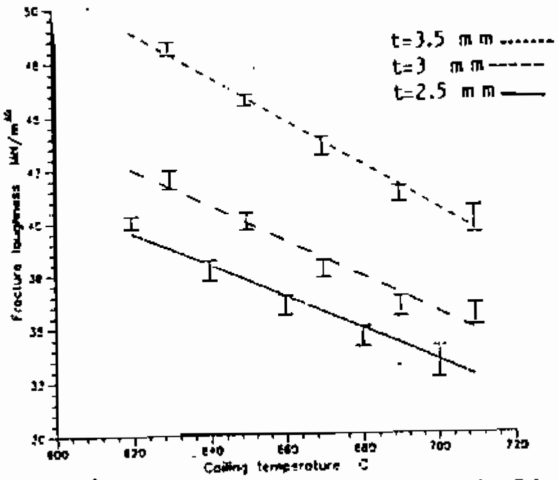

Fig.(2): Effect of coiling temperature on the fracture toughness for hot-rolled steel specimens.

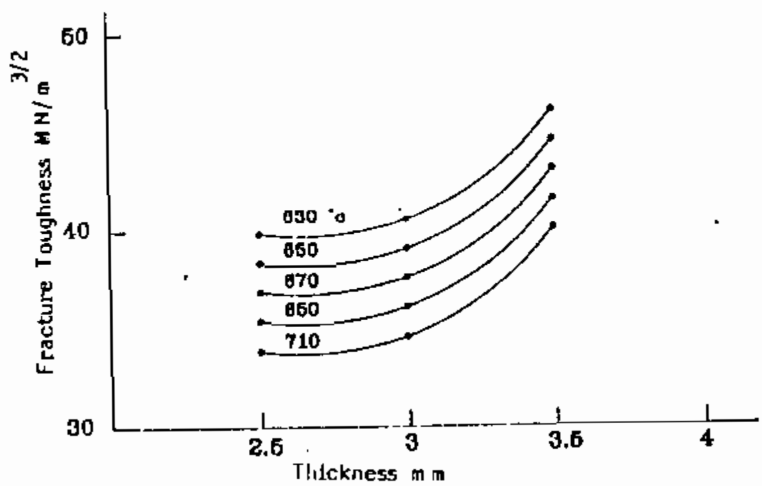

Fig.(3) Effect of thickness on the fracture toughness for hot-rolled steel sheets.

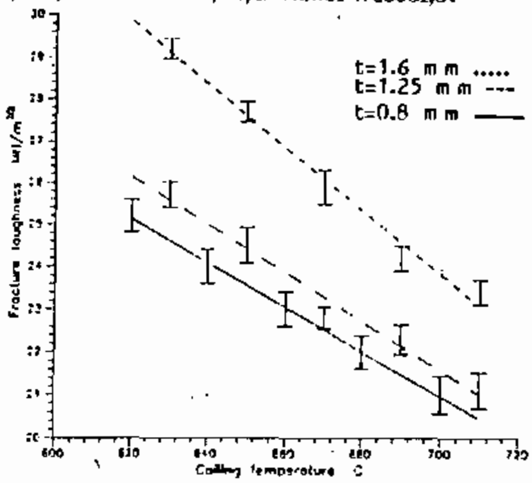

Fig.(4): Effect of coiling temperature on the fracture toughness for cold-rolled steel specimens.

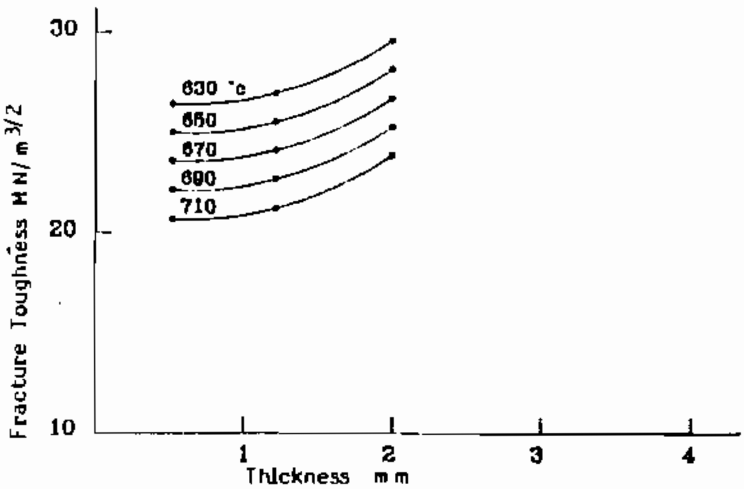

Fig.(5) Effect of thickness on the fracture toughness for cold-rolled steel sheets.

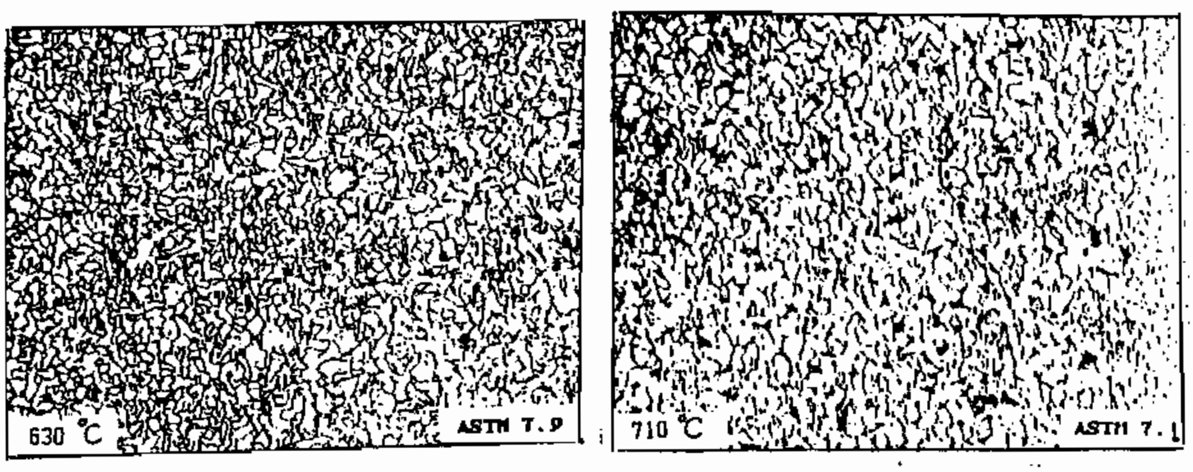

Fig.(6): Effect of coiling temperature on the grain size.