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# Structure/property relationships in HSLA steel with low carbon and manganese and increased silicon content

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The influence of an increased Si and reduced C and Mn content on structure and mechanical properties of HSLA steel plate with low carbon equivalent is investigated. With a C content of 0.06 ... 0.08 % Mn should be ≥ 0.8 %, and Si concentrations up to 1.0 % may be used. On air cooled 30 mm plate (CE (IIW) = 0.30 %, FRT ~ 850 °C) $R_e \leq 420$ MPa and $T_{tr}$ < -70 °C has been obtained.

## INTRODUCTION

Traditionally it is considered that in low-carbon structural steels a Si content of up to 0.3 ... 0.5 % improves strength and toughness, whereas contents above 0.7 ... 0.8 % are detrimental to toughness. Therefore, the Si content in fine-grained HSLA steels is usually limited to ≤ 0.5 or ≤ 0.6 % (see e.g. EN 10025, EN 10113, prEN 10028). On the other hand, most carbon equivalent formulas characterizing the weldability of steels (with respect to hardenability and cold cracking susceptibility in the heat affected zone) consider the Si content either with a low weight factor or not at all. Thus the present work was aimed at investigating the possibility to improve the weldability of HSLA steel without deteriorating its strength, ductility and toughness by lowering the C and Mn concentration which results in a distinct reduction of the carbon equivalent value. The resulting loss in strength is compensated by an increase in Si content taking advantage of the higher solid solution hardening effect of Si (~ 84 MPa/m-%) as compared to Mn (~ 32 MPa/m-%) (1)-(3). The present paper concentrates on structure and mechanical properties of these steels.

## EXPERIMENTAL

The experimental steels were molten either in a 8 kg laboratory vacuum induction furnace or in a 5.5 t electric arc furnace. In the laboratory melts, the Si content was varied between 0.87 and 1.24 %, the Mn between 0.30 and 1.29 %, and the C content was 0.08 ... 0.10 %. Based on the results obtained with these materials the chemical composition of the eight 5.5 t heats was chosen as follows:
0.062 ... 0.070 % C; 0.41 ... 1.17 % Si; 0.94 ... 1.60 % Mn; 0.02 % Ti, 0.03 % Nb; ≤ 0.007 % S; ≤ 0.009 % P; 0.022 % Al; ≤ 0.008 % N. Each of these heats was cast into two 2.7 t ingots having dimensions of about 320 x 770 x 1400 (mm). TM rolling of plate 10 ... 30 mm in thickness was performed using a reheating temperature of 1150 ... 1170 °C, finish rolling temperatures (FRT) of 720...990 °C, and finish rolling reductions of 62.5 ... 75 %. Most plates were air cooled from FRT. In a few cases accelerated cooling with 15 K/s from a FRT of 860 °C to 550 °C was applied. In addition to TM rolling the plates were investigated after normalization at 870 ... 980 °C / ≤ 30 min.

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**RESULTS**

a) Phase transformation behaviour
As is well known, the C, Mn, and Si concentrations influence the phase transformation behaviour of the steels. The $Ar_3$ and $Ac_3$ temperatures increase with increasing Si and decreasing C and Mn content. Their respective values have to be taken into account when fixing the parameters of the TM rolling and normalizing heat treatment.
b) Ferrite-pearlite structure
Mn contributes to both solid solution hardening and ferrite grain refining. A diminution of the Mn content causes an increase of the mean ferrite grain size (fig. 1a) and a broadening of the grain size distribution expressed by the parameter $D_X95/d_X$, i.e. the 95 % quantile of the grain size distribution divided by the mean grain size value (fig. 1b). Si acts on structure and properties mainly via its solid solution hardening effect and has only a weak influence on ferrite grain size (fig. 2).
In TM rolling the FRT should be adapted to the $Ar_3$ temperature. In order to get a fine-grained and homogeneous ferrite-pearlite structure the $\gamma/\alpha$ transformation should start near the end or immediately after finish rolling. At low FRT < 800 °C a strongly deformed structure with ferrite grains elongated in the rolling (x) direction is obtained (fig. 3).
c) Mechanical properties
With increasing Mn content and an adapted FRT a ferrite grain refinement and an increase in strength and toughness is obtained (fig. 4a, b). Considering fig. 1a + b, a Mn content ≥ 0.8 % should be chosen.

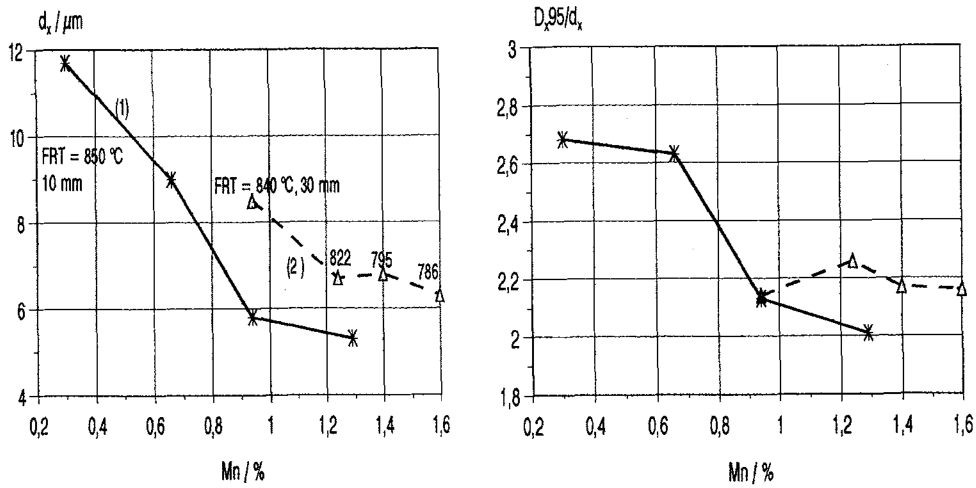


Fig. 1a, b: Influence of the Mn content on ferrite grain size and grain size distribution
(1) 0.10 % C - 1.1 % Si; 10 mm plate (2) 0.068 % C - 0.82 % Si; 30 mm plate

The increase in strength caused by a higher Si content is mainly due to solid solution hardening and therefore connected with a certain decrease in toughness. However, even a 20 mm plate (FRT = 851°C) with 1,2 % Si has a transition temperature of ≤ -60 °C and a yield strength of 450 MPa (fig. 5a, b).The influence of a normalizing heat treatment on strength
and toughness is shown in fig. 6a, b. With increasing normalizing temperature a decrease in strength and toughness is observed which is due to the formation of a coarser ferrite-pearlite structure. Considering the relatively high $Ac_3$ temperature of the steels with high Si and reduced C and Mn content, the temperature and duration of the normalizing heat treatment should be as low as possible to ensure a fine-grained structure after normalization.

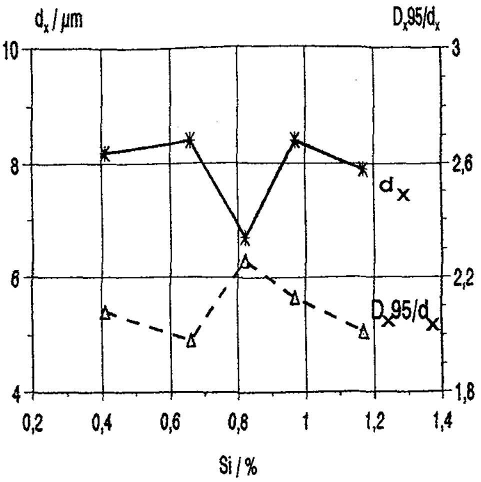


Fig. 2: Influence of the Si content on ferrite grain size and grain size distribution 0.068 % C - 1.22 % Mn; 30 mm plate

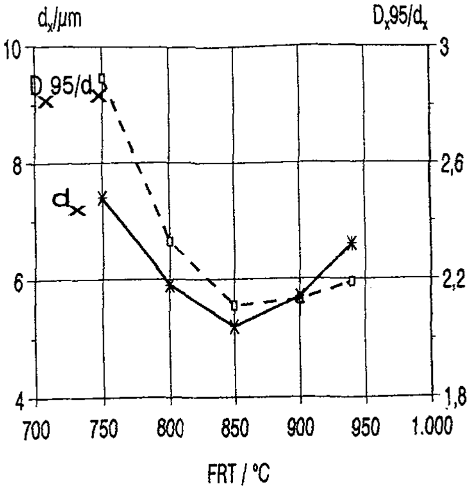


Fig. 3: Influence of finish rolling temperature 0.068 % Si - 0.87 % Si - 1.06 % Mn; 12 mm plate

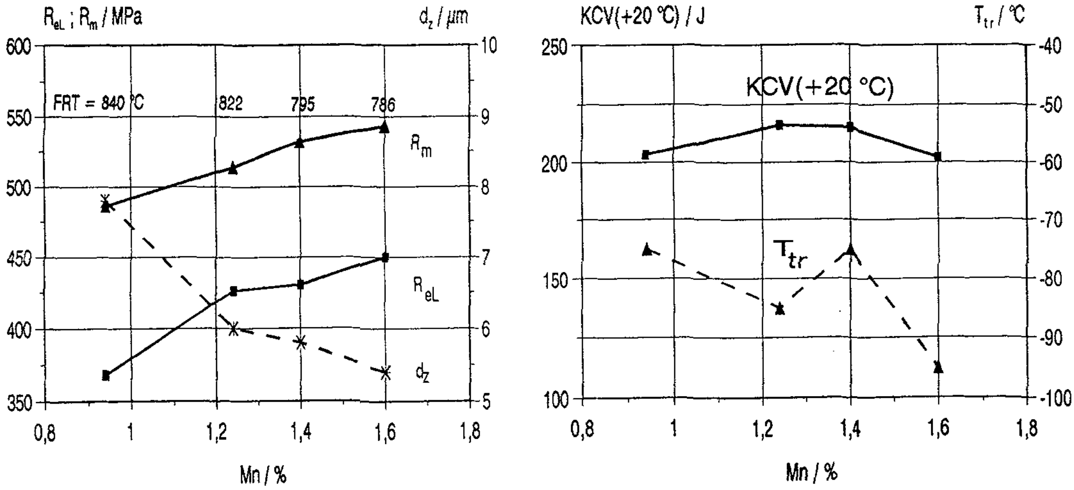


Fig. 4a, b: Influence of Mn on strength, ferrite grain size and impact toughness 0.068 % C - 0.82 % Si; 30 mm plate

## 4. CONCLUSIONS

- In HSLA steel plate with increased Si and reduced C and Mn content a fine-grained and homogeneous ferrite-pearlite structure with favourable combinations of strength and toughness ($R_{eL} \leq 420$ MPa, $T_{tr}$ (27 J) = -70 ... -100 °C) can be obtained if the TM rolling and normalizing conditions are suitably adjusted to the transformation behaviour of the steel.
- With a C content of 0.06 ... 0.10 % the Mn concentration should be not too low (i.e. ≥ 0.8 %), and a Si content of up to 1 % may be used. This gives a CE (IIW) in the order of 0.30 %.
- Whereas Mn contributes to both solid solution hardening and ferrite grain refinement, Si acts mainly as a solid solution hardener and has only a weak grain-refining effect.

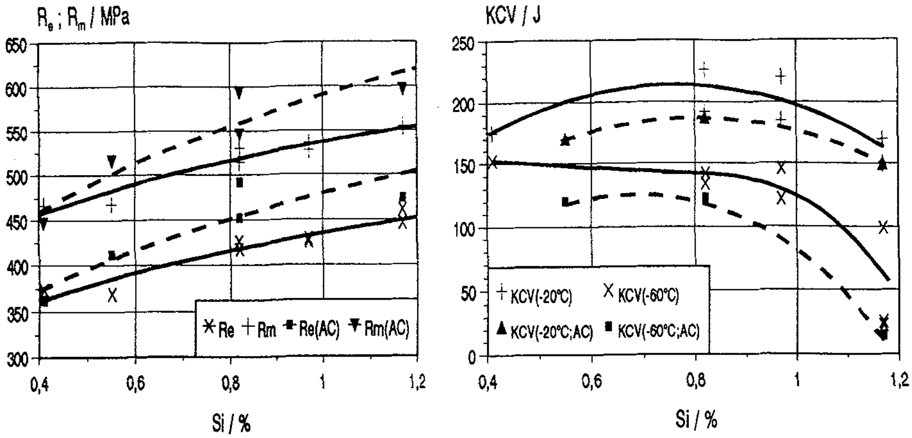


Fig. 5a, b: Influence of the Si content on strength and toughness 0.068 % C - 1.2 % Mn; 30 mm plate. AC: accelerated cooled form FRT (860 °C/15 $Ks^{-1}$/550 °C)

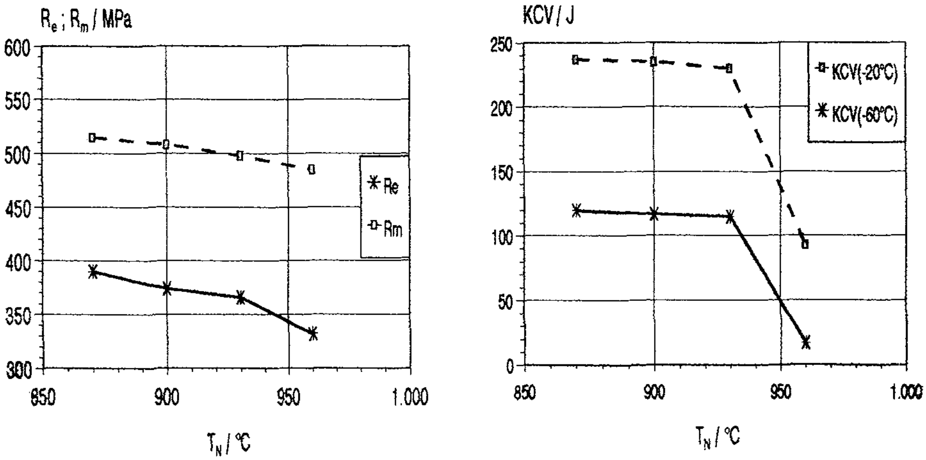


Fig. 6a, b: Influence of a normalizing heat treatment on strength and toughness. 30 mm plate, $t_N$ = 30 min, 0.068 % C - 0.82 % Si - 1.24 % Mn

- The small influence of Si on the hardenability of the steel has the desired effect of a small hardness increase in the heat affected zone of welds.
- First welding experiments (peak hardness, cold cracking behaviour) offered no problems.
- Thus steels with the proposed chemical composition (increased Si and reduced C and Mn content, microalloying with 0.01 ... 0.01 % Ti and 0.03 % Nb) could be a new cost-effective contribution to the family of HSLA steels with good weldability.

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