Surpassing steel performance by creating a very fine grained structure

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Facing overcapacity and global competition steel part production costs must be continuously lowered. To be able to fulfil these upcoming needs new steel concepts are designed and innovative production technologies are developed. Through its systematic development of the thermochemical processing, Steeltec is now able to treat almost any conventional standard steel and significantly improve its properties. An ultrafine grain size is achieved by carefully controlled combination of heat and mechanical force, producing steel properties that could otherwise only be achieved by high alloy concentrations or by complex and costly additional processing stages. The possibilities of this technology are presented on the bar steel product 7MnB8. After austenising and a single extreme deformation step the ductile-to-brittle transition temperature can be shifted significantly to lower temperatures for 7MnB8. The observed temperature shift is due to the ultrafine microstructure attained after processing. The fine grain size in hot-rolled and air-cooled 7MnB8 bar resulted in the 27 J criteria to be fulfilled at temperatures as low as −101°C. Additionally, crack free cold bending is possible at room temperature using a version of the 7MnB8 providing high strength and high toughness.

KEYWORDS: BAR STEEL – GRAIN SIZE – IMPACT STRENGTH – DEFORMATION – LOW TEMPERATURES

Introduction

In the past bright bar drawn steels from Steeltec have been developed to enhance the properties strength and toughness using dislocation strengthening, microalloying elements and bainitic steel grades.

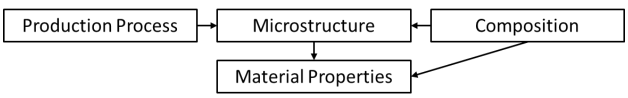

Fig. 1 – Methods to improve material properties

The markets slow acceptance for new steel grades and compositions, plus the ongoing need for further quality improvements, was incentive to apply a new method of improving the properties by modifying the process.
Grain-boundary strengthening, as expressed by the Hall-Petch relation, is a fundamental mechanism for strengthening materials. Steeltec's new long bar manufacturing process achieves a considerable reduction in grain size and thus enables the material properties of conventional steels to acquire previously unobtainable values [1,2].
The technology combines a high-reduction forming stage with a single-bar heat treatment line. This allows the production of an ultrafine microstructure, due to precise control of temperature, deformation and cooling [3]. For low-alloy carbon steels it is desirable to achieve a high degree of deformation in one or a small number of rolling steps in order to impede recovery

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[4]. The benefits of applying ultrafine grain steels produced by multipass warm calibre rolling for the mechanical properties of steel have been published e.g. Murty and Torizuka [5].
Steel bars produced using this technology are an alternative to higher alloyed QT-steel grades, as this new technology significantly boosts the performance of low-alloy steel grades.

Experimental
For the experiments a microalloyed low carbon steel, of type C-Mn-B was used. The chemical composition is shown in Table 1. The material, which was produced by a conventional rolling process, had a yield strength of ~530 MPa and a tensile strength of ~690 MPa. Its elongation at fracture was ~19% and the ductile-to-brittle transition temperature was in the range of 30–40 °C.

Tab. 1 – Material prior treatment, chemical composition in weight %, $Rp_{0.2}$ and R_m in MPa, A_5 in %

	C	Si	Mn	P	S	B	$Rp_{0.2}$	R_m	A_5
7MnB8	0.07	0.20	1.90	0.01	0.01	0.0025	530	690	19

Results and discussion
The aim of this study was to determine how the new manufacturing process changes the structure and mechanical properties of the steel. The first area investigated was the influence of austenising temperature on the impact strength.
The first step involved measuring the austenite grain size at different temperatures. This is shown exemplary on the steel grade 7MnB8. A grain size of approximately 11 µm was found in the temperature range 950 °C to 1150 °C. At higher temperatures, grain growth started to occur.
The austenising temperature range 950–1100 °C was used for the production line trials. The bars were heated to the desired temperature by inductive heating, whilst monitoring the temperature optically. The bars were then cooled to < 800 °C before forming. The deformation was achieved in one step [3]. After deformation, the bars were cooled in still air. The degree of deformation selected was $\varphi \geq 0.3$. A marked increase in impact strength was observed with decreasing austenising temperature.
The degree of deformation, needed to achieve the desired impact strength was defined by searching for the minimum degree of deformation needed to achieve the desired impact strength and the maximum degree of deformation that does not harm the material. As quality criteria a minimum of 27 J was aimed for. For 7MnB8 the deformation degrees were altered between 0.3 to 0.6. Fig.2 presents the results achieved using an austenising temperature of < 1000 °C and a temperature before forming of < 800 °C.
The marked influence of increasing deformation on the impact transition temperature (ITT) of steel was published by Pickering in 1975 who stated, that continuing heavy-rolling reductions to very low temperatures can produce a further improvement in strength and ITT, due to additional refining of the grain size and formation of a very fine polygonised sub-structure [6].

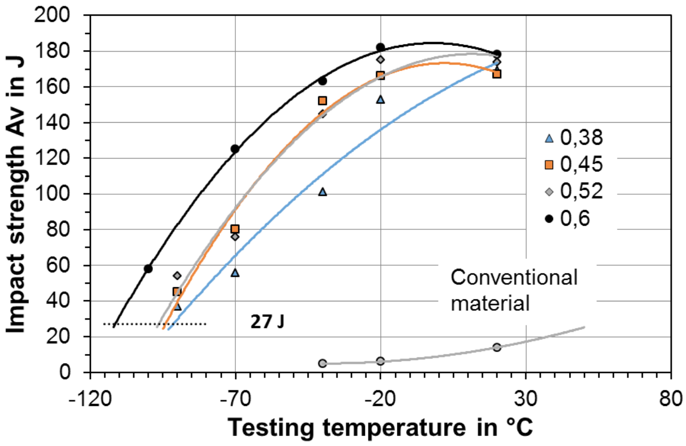

Fig. 2 – Impact strength curves for different degrees of deformation

For the 7MnB8 steel grade examined here, the impact transition temperature shifted to approximately -120 °C when the material underwent austenisation < 1000 °C and a forming temperatures < 800°C was used. The impact strength of bars that had been rolled on the new processing line showed a distinct upper shelf in comparison with material from a conventional rolling process. For the deformation range studied and with air cooling, the upper shelf (ductile fracture) was at approximately 160 J. The decrease in the impact strength curve starts at around - 20°C.

The greater the degree of deformation imparted to the material, the lower the temperature at which the ductile-to-brittle transition (ITT) occurs. Even under severe plastic deformation, with a degree of deformation of 0.6, no material defects in the form of microcracks were revealed by microscopic inspection.

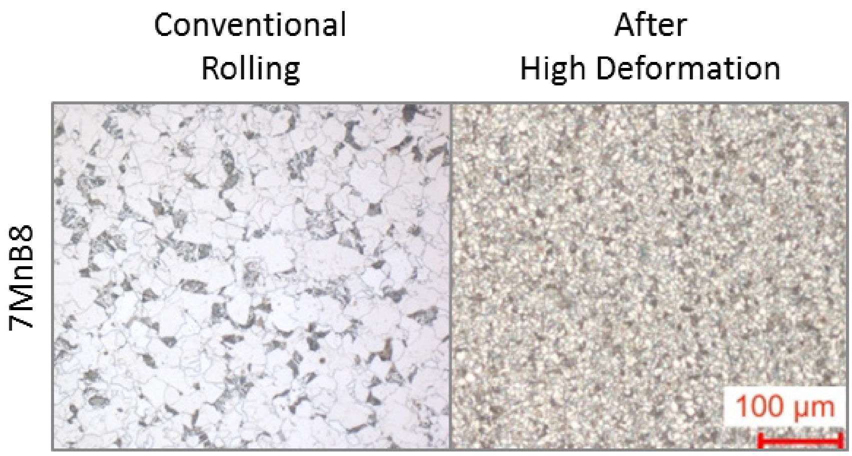

Fig. 3 – Microstructure of 7MnB8 after conventional rolling and after the high deformation process, degree of deformation of 0.6 and air cooling

The shift of the ITT is thought to be caused by increasing grain refinement, see Fig. 3.

The conventional rolled material can exhibit a structure composed of both ferrite and pearlite. A structure of ferrite and pearlite was observed under the light microscope for the 7MnB8 after the high deformation process step.

The superior mechanical properties of the steel produced on the new processing line are related to the microstructure, which contains most probably increasing amounts of polygonal ferrite with increasing degree of deformation. Starting from the conventional rolled material, the surface area of the austenite grain boundary area increases during deformation, due to pancaking [7]. As a result of the enhanced defect density along the grain boundaries of the deformed grains, polygonisation can begin and may well also increase the number of nucleation sites inside the grain. This will accelerate the ferrite transformation. It is also possible that the strain induced by the deformation causes intra-granular ferrite nucleation that will further contribute to grain refinement [7].

In addition to the improved impact strength, we also studied the mechanical strength achievable in the austenitisation temperature range 900–1100 °C. The tensile strength and the yield strength showed a relatively small change of about 50 MPa to 100 MPa. The elongation varied by approximately 5%. Tests were therefore performed that included an increased amount of water cooling after the deformation stage ($\varphi = 0.6$), an austenitisation temperature of < 1000 °C and a temperature before forming < 800 °C.

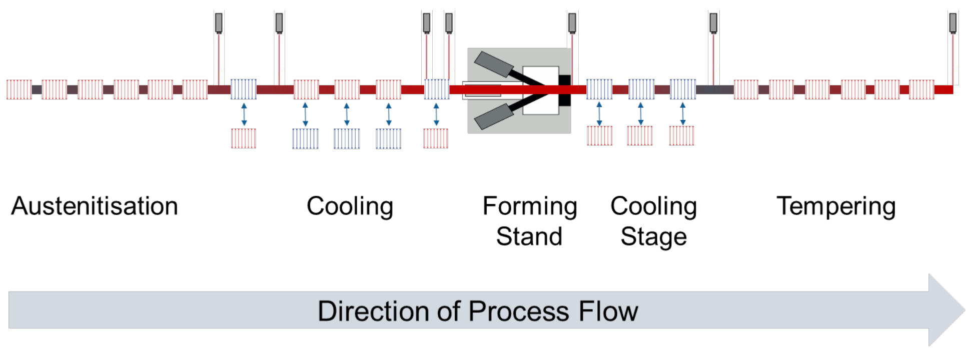

Fig. 4 – Processing line for the heat treatment and deformation step

The production process can use various cooling elements in close proximity after the deformation step, see Fig. 4. The cooling step is an additional element, with which the process parameters can be altered. A variation of mechanical properties achievable using a technology with a severe plastic deformation step combined with a single-bar heat treatment line, due to different process parameters is shown in Tab. 2 for the 7MnB8.

Tab. 2 – Various mechanical properties achievable with different process parameters for 7MnB8 in comparison to 42CrMoS4

	Material Condition	$R_{p0.2}$ [MPa]	R_m [MPa]	A_5 [%]	$A_{V,RT}$ [J]	T_{27} [°C]
1.5519	Hot rolled	≥400	690-750	≥15	<30	20
	moderate strength, extreme low temperature toughness	425	700	22	≥150	-101
	high strength, higher low temperature toughness	625	800	20	≥150	-101
	extreme strength, high low temperature toughness	825	1000	13	≥100	-50
	42CrMoS4 +QT	≥750	1000-1200	≥11	≥35	

Due to the additional cooling step the structure of the 7MnB8 changed and the grain size could no longer be determined under the light microscope. An analysis was performed under the scanning electron microscope. The sample used had a yield strength of 644 MPa, a tensile strength of 809 MPa and an impact strength at room temperature of 215 J. The sample exhibited a granular bainitic structure. The bainitic microstructure was characterised on the basis of the unified terminology introduced by Zajac et al. [8].
Misorientation maps produced by electron backscattered diffraction (EBSD) from the near surface region and from the core zone were used to gain information of the boundaries and the orientation of the grains. The EBSD maps contain the diffraction data from an area of roughly 15 μm_2. By measuring the orientation of the adjacent grains, the grain boundary crystallography was determined. A step size of ~0.07 µm was used. For statistical purposes, any boundary exceeding 15° was considered a boundary. The EBSD analysis revealed a high amount of boundaries > 15°.
The conventional rolling mill material displays an average ferrite grain size of approximately 13.8 µm [9]. After forming with a deformation degree of 0.6, the grain size was considerably reduced to below 5 µm.

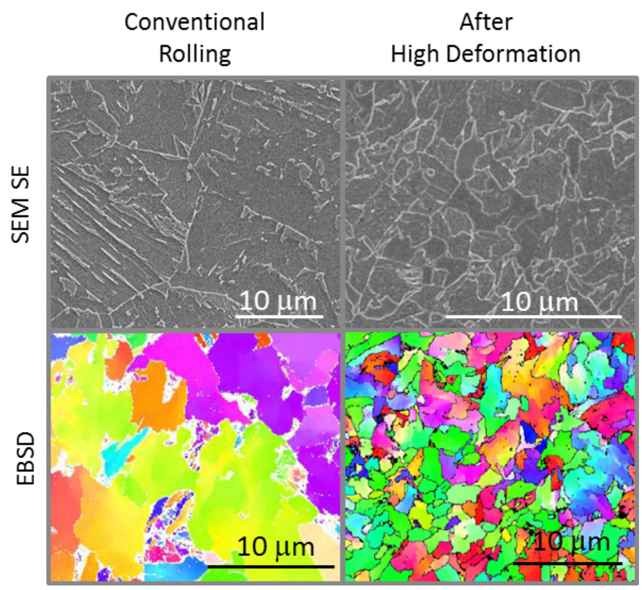

Fig. 5 – SEM and EBSD images of 7MnB8 with a $Rp_{0.2}$ = 644 MPa, R_m = 809 MPa and $A_{v,RT}$ = 215 J

The conventional rolled steel grade 7MnB8 has been used for cold heading applications [10]. To see if further forming after high deformation of the 7MnB8 was possible, a 18 mm bar with a yield strength of 990 MPa, a tensile strength of 1100 MPa and an elongation at rupture of 13 % was used for cold bending. The bending radius was 10 mm. The strength level was similar to a 42CrMoS4, see Tab. 2. Samples after cold bending up to 150° were metallographically investigated and no cracks were visible. This positive result is thought to be related to the fine grain size.

Fig. 6 – Bending test of a 18 mm bar of 7MnB8 with Rp0.2 = 990 MPa, Rm = 1100 MPa and A5 = 13%

Conclusions

. A production process was introduced that enables to adjust the mechanical properties within a wide range after austenising and a single extreme deformation step

. The adjustment of the process parameters step by step was investigated for the steel grade 7MnB8

.The high degrees of deformation enables a very small average grain size to be achieved. An average grain size < 5 µm was observed

.The impact transition temperature can be shifted considerably to lower temperatures

.The notch impact energy for a version of the high deformed 7MnB8 is ≥ 150 J at room temperature

.Good formability even at high strength

Acknowledgments

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