

## INFLUENCE OF SILICON AND MOLYBDENUM ON STRENGTH AND PLASTICITY OF 0.1C STEEL SHEET

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### Abstract

Low carbon high-strength steel sheets are in scope of the material research mainly used as structural materials for automotive industry. Cold forming is the most prominent technology of achieving the final shape of the parts made of thin sheet. This requires sufficient plasticity of the material so that the forming procedure can be performed without sheet fracture. High strength steels are attractive due to possibility of weight saving; however, their higher strength comes with a reduction of plasticity. Especially widely used dual and complex phase steels, providing an exceptional combination of plasticity and strength, are not performing well during forming due to their susceptibility to an edge fracture. It emerged that this feature is caused by alternation of hard martensite and soft ferrite in their structure causing crack propagation by separation of these phases. This experiment is aimed at development of a high-strength low-carbon steel sheet of a homogeneous low-tempered martensite microstructure with a tensile strength in an interval of 1000-1200 MPa. This strength is comparable with the highest grades of dual and complex-phase steels. However, the homogeneous microstructure gives an advantage in the formability, which can be crucial factor for the cold forming operation. Influence of different concentration of Si and Mo was examined by tensile test and hole expansion test for 0.8 mm thick sheets.

**Keywords:** High strength steel, martensite, formability, hole expansion test

### 1. INTRODUCTION

High strength steel sheets are massively used semi-products in automotive and other industry branches. One of the main technologies of their manufacturing is punching from the initial strip and cold forming of the final product shape. This demands sufficient plasticity from the sheet and stretchability of the sheared edge. Dual- and complex-phase steels dominates the landscape of high strength steels with strength above 1000 MPa for last decades due to their excellent combination of strength and ductility [1]. However, presence of soft and hard phases in their structure proved to be detrimental for their edge stretchability [2] and is their limitation in their use in cold forming process [3-5].

This article builds on the long history of low-carbon martensite steels, represented e.g., by the 22MnB5 grade used in a martensitic state [6-8]. This grade is usually not used for cold forming operations due to its too high yield stress but decrease in carbon content could soften the martensite to the acceptable strength value around 1200 MPa and the single-phase structure will have prospect of possible good formability [9]. Si content was varied from 0 to 2 wt% to study influence of this solution strengthening element on the mechanical properties [7]. Mo was added into the composition to test its influence onto the austenite grain refinement during quick austenitization of a thin sheet.

## 2. MATERIALS AND METHODS

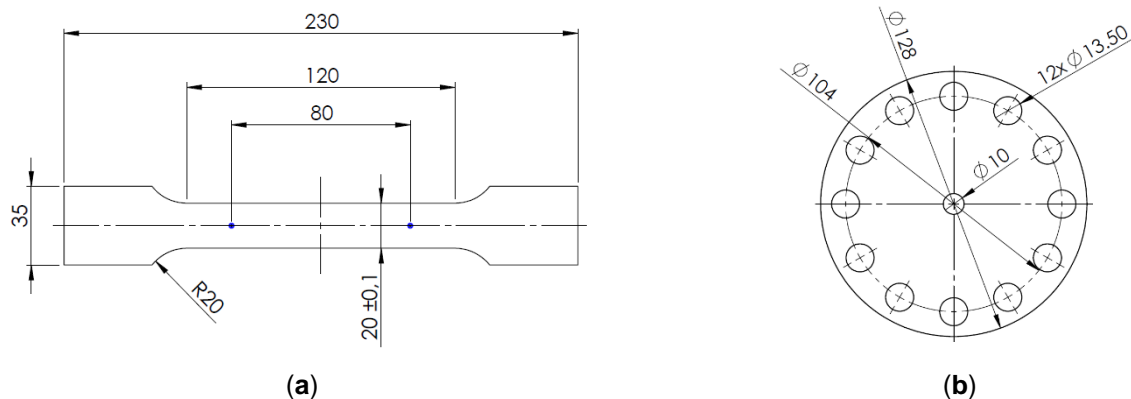
Four experimental steels were produced for this experiment. They were melted in the vacuum induction furnace and casted into steel molds. Ingots of a gross weight 500 kg were obtained. Chemical composition of the experimental steels is in the **Table 1**. Si and Mo were the elements which content was intentionally varied. Content of other elements were kept as constant as possible among the melts.

**Table 1** Chemical composition of the experimental steels. All concentrations are given in weight %.

Material	C	Si	Mn	Mo	P	S	B	Ti	Fe
0Si	0.10	0.19	2.03	0.051	0.011	0.001	0.0030	0.025	Bal.
1Si	0.11	1.00	2.08	0.046	0.017	0.002	0.0030	0.023	Bal.
2Si	0.11	1.91	1.92	0.040	0.018	0.002	0.0021	0.025	Bal.
2SiMo	0.10	1.98	1.99	0.141	0.020	0.002	0.0029	0.024	Bal.

Ingots were hot forged in a hydraulic press into billets with 300 x 85 mm cross section. The billets were machined to remove scales and subsequently hot rolled by two-high reverse rolling mill into sheets 10 mm thick and 300 mm wide. The sheets were then milled to remove scales and cold rolled into sheets 300 mm wide and 0.8 mm thick. The cold rolling was performed by rolling mill in four-high configuration with two recrystallizations annealing during the process.

Specimens for mechanical testing were cut from the cold rolled sheets by a waterjet cutting. The specimens were then quenched and tempered. Austenitization was performed in an electric atmospheric furnace at the temperature 970 °C. The specimens were inserted into the furnace for the period of 3 minutes mounted on the jig so that the area of interest for the testing of the specimen was not in contact with the furnace and was heated by the radiation and the atmosphere from both sides. The specimens were removed from furnace after 3 minutes and immediately quenched in a water bath. Tempering was performed at 210 °C for 20 minutes. All specimens from all materials were treated by the same regime.



**Figure 1** Drawings of the a) tensile test specimen, b) hole expansion test specimen.

Quasistatic tensile test was performed at room temperature using dog bone shaped specimens with gauge length 20 mm (**Figure 1a**). The sides of the gauge length were machined after the thermal treatment. Yield stress (YS), ultimate tensile strength (UTS), total plastic elongation at length 80 mm ( $A_{80}$ ) and reduction of area (ROA) were measured. Three specimens were tested for each material according to the standard EN ISO 6892-1.

Hole expansion test was performed according to standard ISO 16630. The drawing of the specimen is in the **Figure 1b**. The central hole for the expansion was created by punching. The sheet deformation and crack

formation were measured by digital image correlation system ARAMIS. Hole expansion ratio (HER) was computed from the results according to the standard as equation (1):

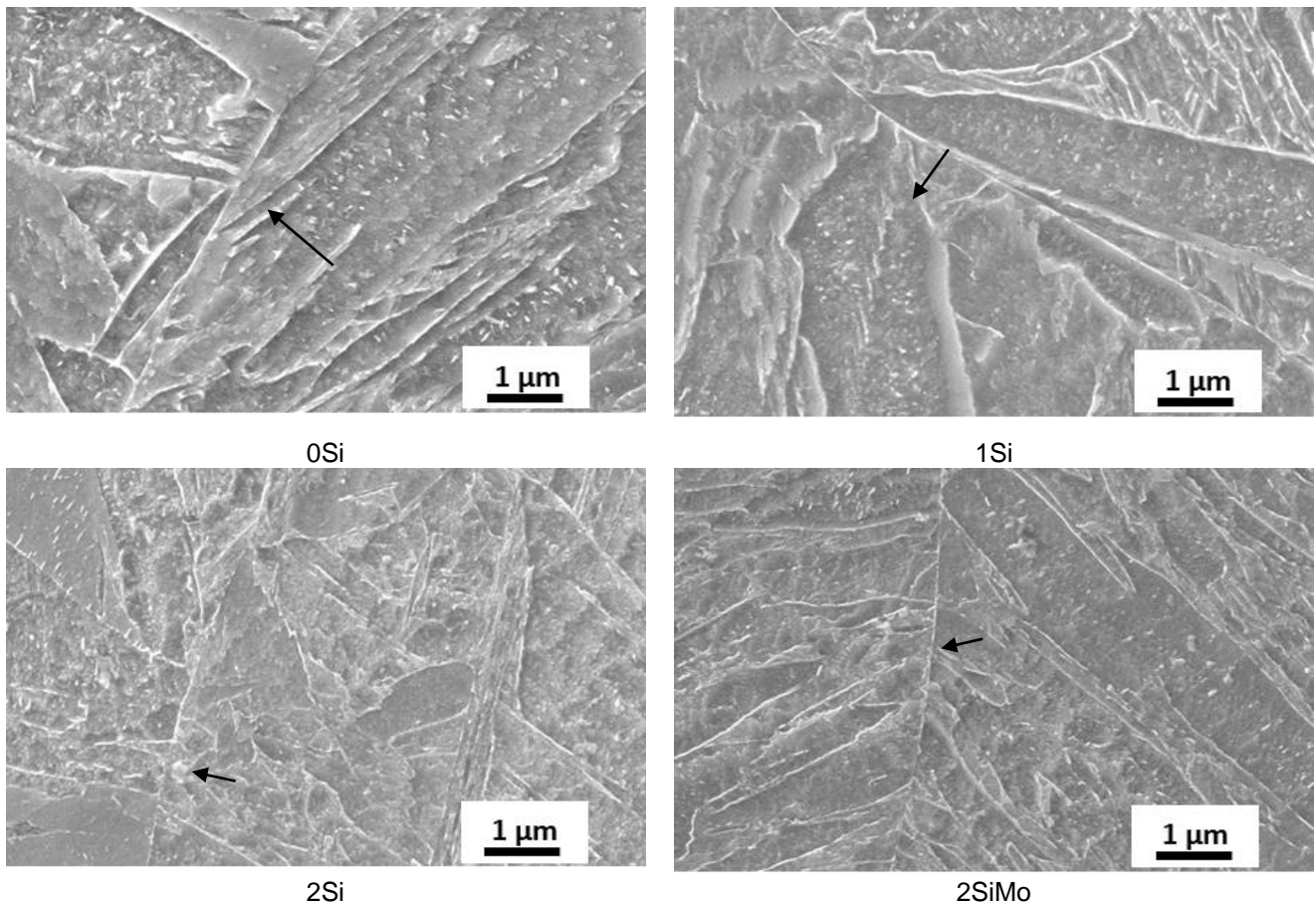
$$HER[\%] = \frac{D_e - D_0}{D_0} \cdot 100 \quad (1)$$

where  $D_0$  is the initial hole diameter and  $D_e$  is expanded hole diameter in the moment of the hole edge cracking. Six samples were tested for each material.

Metallography analysis was performed on the longitudinal sections of the heat-treated sheets. Sections were mechanically ground and polished. Microstructure was revealed by etching in Nital etchant. Sections were observed in scanning electron microscope (SEM) JEOL JSM IT-500HR at 15 kV acceleration voltage. Images were acquired in a secondary electron signal.

### 3. RESULTS AND DISCUSSION

Microstructure of all materials was composed of tempered martensite. SEM images shows martensite crystals and prior austenite grain boundaries (**Figure 2**).

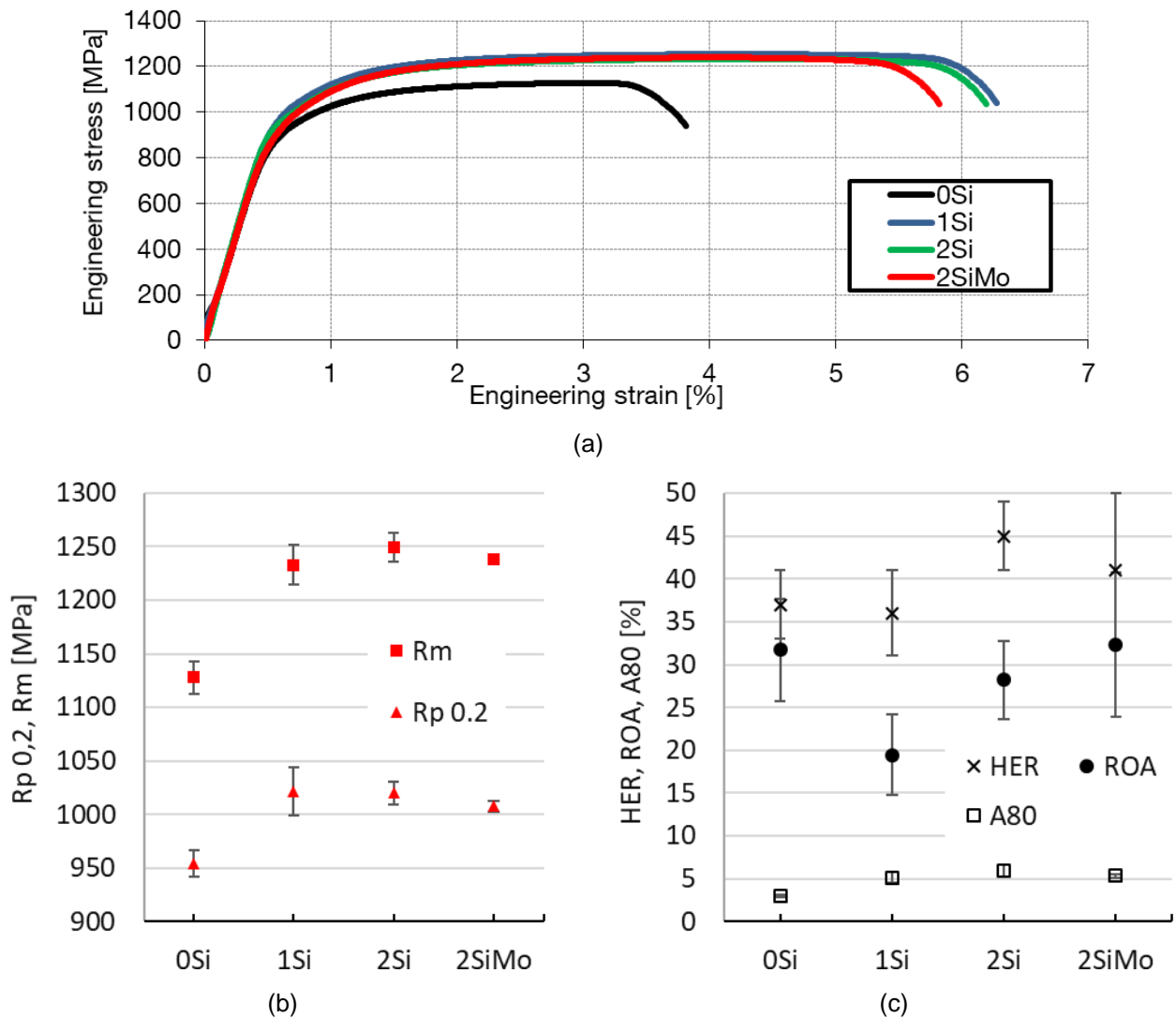


**Figure 2** Microstructure of the experimental steels. Tempered martensite with visible prior austenite grain boundaries (marked by arrows)

Martensite crystals shape and prior austenite grain size were seemingly the same for all experimental steels. Carbides precipitated in the martensite crystals during the tempering in all samples.

Tensile tests revealed that all materials exhibit continuous yielding behavior. Typical stress-strain diagrams are shown in **Figure 3a** for experimental steels. **Figure 3b** shows influence of alloying elements on the YS

and UTS. Higher Si content caused their increase, however only between 0% Si and 1%Si was this increase significant. Further increase in Si content did not cause YS to rise, only slight rise in UTS. **Figure 3c** shows influence of alloying elements on the plasticity of experimental steel. Ductility interestingly increased together with strength with higher Si content and reached maximum values at 2 wt% Si. There was observed no traditional “trade-off” between strength and ductility, both parameters are higher. Increased Mo content had no significant effect on the mechanical properties. ROA exhibited no clear trend with increasing Si content.



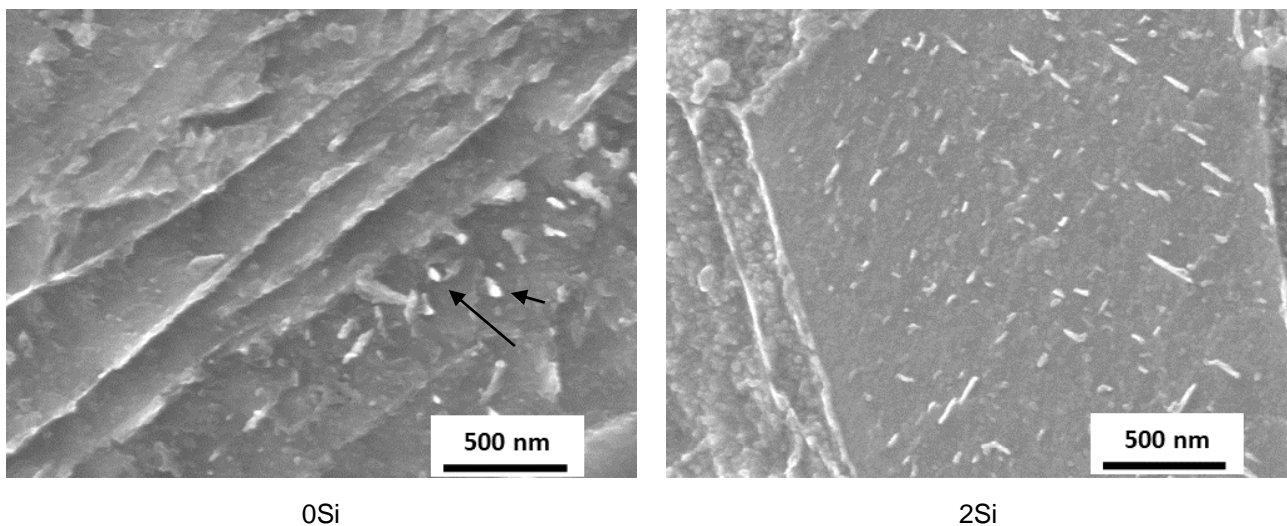
**Figure 3** Results of tensile testing and hole expansion tests

HER values are depicted in **Figure 3c**. Their value seemingly followed the ROA value from the tensile test, being in agreement with a literature, putting emphasis on the post-maximum force plasticity as the most important material characteristics from tensile test in determining the HER value.

The strengthening of the steel by Si alloying is expectable as Si is an element causing increase of a friction stress in a ferrite lattice. This can be projected into this case, where the matrix is a matrix of low-tempered martensite. The strengthening rate was 70 MPa/(wt%Si) on YS between 0 and 1wt% Si and practically non-existent between 1 and 2wt.%. This can be attributed to the fact, that the matrix is presumably far from equilibrium ferrite bcc lattice and that contains also other atoms than Si in a solid solution. The interaction of Si and Mn or B atoms can cause a non-linear strengthening even at low alloying elements concentration.

The same can be said about the interaction of solute atoms with lattice defects, namely dislocations. 210 °C tempering allows us to infer that the dislocation density can be still significant in the martensite matrix.

Besides solution strengthening, the Si reportedly influences another source of strengthening in a low tempered martensite - the precipitation strengthening. Carbon escapes from the supersaturated fresh martensite during tempering and forms tempering carbides, which ideally precipitate inside the martensite crystals. Precipitation strengthening of these crystals than partially compensates for loss of solid solution strengthening from the carbon atoms originally dissolved in fresh martensite crystal lattice. Si is known for its hindering effect on carbide precipitation in steel due to its insolubility in carbides. **Figure 4** shows detailed view into the interiors of martensite crystals and their boundaries in the 0Si and 2Si steels. There was a noticeable difference in appearance of the tempering carbides inside the martensite crystals. 0Si steel contained plate-like thin particles as well as globular ones, often connected with some thin plate-like carbide (marked by arrows in **Figure 4**). 2Si steel did not contain any of these globular particles in the martensite crystals, all particles were in form of thin plates. This could be the effect of Si, preventing spheroidization of the tempering carbides and keeping their plate-like shape. This can have obviously consequences in mechanical properties because type of the precipitate strongly influences its strengthening effect - via its density, shape factor or coherence.



**Figure 4** Details of the tempered martensite structure

It is interesting, that the Si content enhancement from 1 to 2 wt% caused increase in plasticity and not in YS. Si did not influence the absolute value of lattice strengthening in the region of (quasi-)elastic region of the tensile test, but influenced the way the martensitic matrix resisted deformation past the YS point when dislocation were flowing through the martensite crystals.

#### 4. CONCLUSION

Results of the mechanical tests showed that Si strengthened low-tempered low-carbon martensite only in concentration up to 1 wt%. Further increase in Si content up to 2 wt% did not cause further strengthening.

Si rising content also rose the ductility of the sheet and in 2 wt% content also rose slightly the hole expansion ratio. Increasing of both the strength and the plastic properties indicates highly positive influence of Si on the structural performance of the martensitic sheets. Addition of Mo did not have significant influence on the mechanical properties and did not cause refinement of austenite grain during fast austenitization.

This behavior rises an interest in deeper study of Si influence on the steel plasticity. The plasticity is in scope of interest for high strength steel sheets being often their limiting property for use in metal-forming industry.

## ACKNOWLEDGEMENTS

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