

INVESTIGATION OF REPLACING NIOBIUM WITH TITANIUM IN S355MC STEEL WHILE MAINTAINING THE STANDARD MECHANICAL PROPERTIES

¹Ramóna VESZPRÉMI, ²Gábor SZABÓ

¹HUN-REN–ME Materials Science Research Group, H-3515 Miskolc-Egyetemváros, Hungary, EU,
veszpremi.ramona@student.uni-miskolc.hu

²University of Miskolc, Faculty of Materials and Chemical Engineering, H-3515 Miskolc-Egyetemváros, Hungary, EU, gabor.szabo@uni-miskolc.hu

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Abstract

Niobium is a widely used microalloying element in HSLA steels; however, supply- and cost-related risks justify the investigation of alternative solutions. The aim of this study was to determine whether complete or partial replacement of niobium with titanium is feasible in EN 10149-2:2013 grade S355MC steel while maintaining the mechanical properties required by the standard. Three alloying concepts were compared under industrial conditions: conventional Nb microalloying, Ti microalloying instead of Nb, and combined Nb+Ti microalloying. The resulting coils were evaluated with respect to mechanical properties, chemical homogeneity, SEM observations and cost aspects.

The results showed that the upper yield strength and tensile strength of the Ti-microalloyed S355MC steels were lower than those of the Nb-microalloyed reference material, while elongation remained nearly unchanged and impact energy values were more favorable. Despite the scatter of the mechanical test results, the Ti-microalloyed steels remained within the standard limits specified for S355MC in all cases. These findings indicate that this concept may be industrially applicable; however, the observed inhomogeneity requires further technological refinement.

From an economic point of view, titanium may represent a favorable alternative. The cost analysis showed that FeTi was significantly less expensive than FeNb, and that considerable cost reduction could still be achieved even if about twice as much titanium was required to obtain the desired mechanical properties. Based on the results, replacing niobium with titanium appears realistic, provided that further technological optimization is carried out while maintaining the standard properties of the steel grade.

Keywords: S355MC, HSLA steel, niobium, titanium, microalloying, mechanical properties

1. INTRODUCTION

Microalloying plays a key role in the development of HSLA steels, since favorable strength and formability can be achieved through the combined effects of grain refinement, thermomechanical processing and precipitation strengthening [1-3]. In automotive applications, it is particularly important that the applied steel provides adequate yield strength, tensile strength, ductility and impact toughness while remaining economically feasible [1].

Niobium is one of the most effective microalloying elements in HSLA steels because it strongly retards austenite recrystallization, contributes to grain refinement and promotes precipitation strengthening [2-4]. Titanium also has a pronounced metallurgical effect; however, its behavior cannot be regarded as identical to that of niobium. The effect of titanium is strongly influenced by its high affinity to nitrogen, oxygen and sulfur,

as well as by its nitride- and carbide-forming tendency [2,5]. In combined Nb+Ti microalloying, complex precipitation conditions may develop, which directly affect the final mechanical properties [6].

Due to the increasing cost of alloying additions and the uncertainty of raw material procurement, it is justified to investigate whether niobium can be partially or fully replaced by titanium in EN 10149–2 grade S355MC steel. The aim of the present work was to compare three industrial alloying concepts: Nb microalloying, Ti microalloying and combined Nb+Ti microalloying in S355MC steel, from mechanical, metallurgical and economic points of view. For the qualification of S355MC, the longitudinal specimens are decisive; according to EN 10149-2:2013, the required standard values are $R_{eH} \geq 355$ MPa, $R_m = 430\text{--}550$ MPa, and $A_5 \geq 23$ % for thicknesses of 3 mm and above [7]. In the present study, impact energy was also included in the evaluation, since this property formed part of the experimental assessment of the investigated heats. The mechanical properties considered in the evaluation are summarized in **Table 1**.

2. MATERIALS AND METHODS

Three industrial heats of S355MC steel produced according to different alloying concepts were investigated: a conventionally Nb-microalloyed heat, a Ti-microalloyed heat produced instead of Nb, and a combined Nb+Ti microalloyed heat. Mechanical characterization was based on upper yield strength, tensile strength, elongation after fracture and impact energy. The evaluation of the mechanical test results was carried out according to the requirements of EN 10149–2 [7]. The mechanical property limits considered for the qualification of S355MC steel are summarized in **Table 1**. Chemical homogeneity was evaluated by OES analysis, covering C, Mn, Si, S, P, Cu, Cr, Ni, Al, Mo, Nb, V and Ti contents. Metallurgical interpretation was supported by SEM investigation and inclusion assessment. Economic evaluation was based on the procurement costs of FeNb and FeTi wires and on the calculated microalloying costs of the industrial heats.

Table 1 Mechanical properties considered in the evaluation of S355MC steel, based on EN 10149-2:2013 and the impact energy criterion applied in the present study

Mechanical properties			Impact energy, KV [J]
R_{eH} [MPa]	R_m [MPa]	Elongation after fracture A_5 [%]	-20 °C
		$3 \leq h$	$6 \leq h$
min. 355	430-550	min. 23	min. 40

In the following, the measured mechanical properties are discussed with respect to the standard limits summarized in **Table 1**.

3. RESULTS AND DISCUSSION

The mechanical evaluation of the investigated S355MC steel grade showed that the Nb-microalloyed reference material exhibited the most stable mechanical behavior. The Ti-microalloyed coils generally showed lower and more inhomogeneous mechanical properties; however, they still fulfilled the relevant standard requirements. The combined Nb+Ti microalloying concept also complied with the mechanical requirements and showed lower inhomogeneity than the fully Ti-microalloyed variant.

A detailed comparison of the mechanical results obtained for the three alloying concepts is presented in **Figures 1-4**.

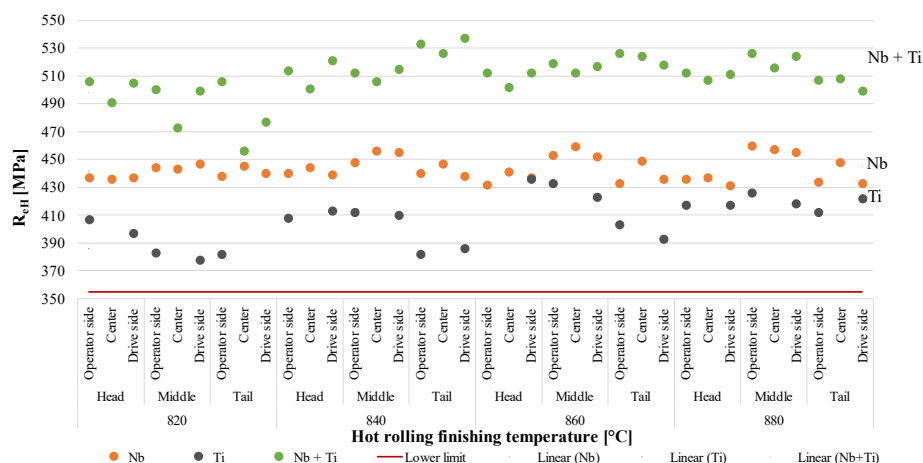


Figure 1 Comparison of upper yield strength

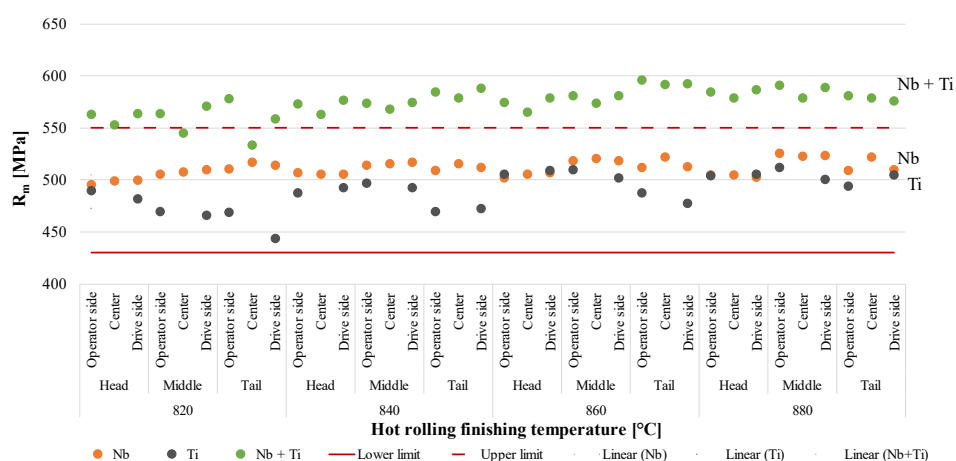


Figure 2 Comparison of tensile strength

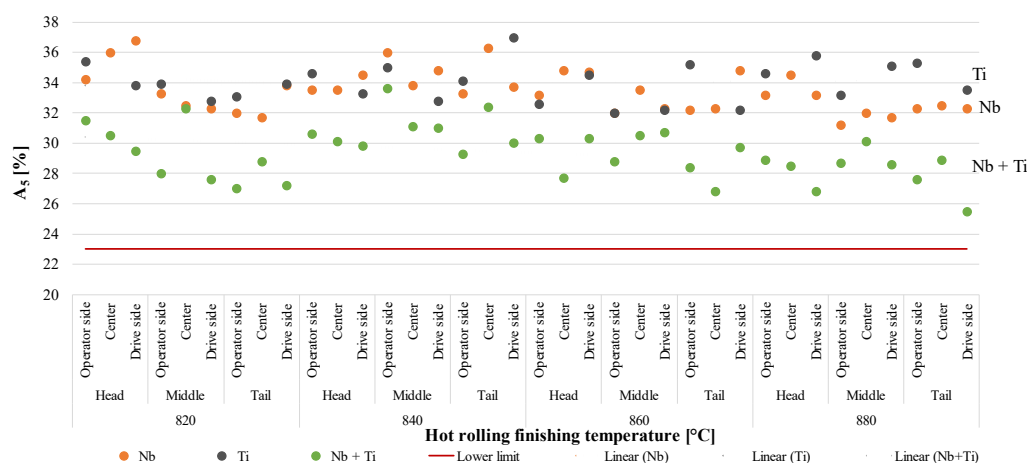


Figure 3 Comparison of elongation after fracture

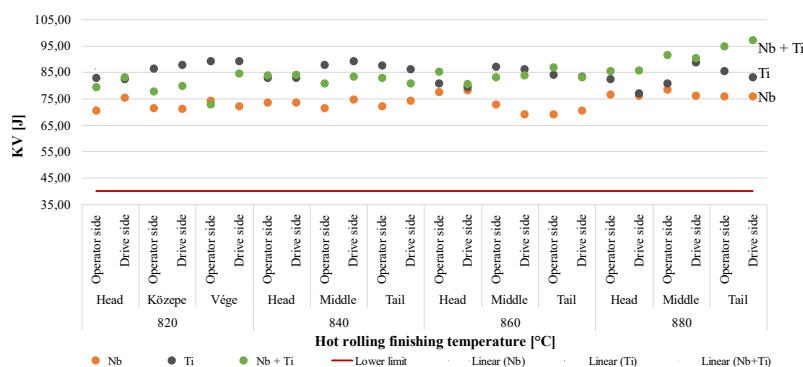


Figure 4 Comparison of impact energy values

Based on **Figures 1-4**, it can be concluded that the Nb-microalloyed reference material showed the lowest scatter in mechanical properties. In the case of the Ti-microalloyed coils, the upper yield strength and tensile strength were generally lower than those of the Nb-microalloyed reference material; however, the elongation after fracture and impact energy values remained above the standard limit values. In the combined Nb+Ti microalloying concept, the strength-related properties were more favorable, while the mechanical inhomogeneity was lower than in the fully Ti-microalloyed material. Based on the presented results, full Ti-based substitution may represent a favorable option from the economic point of view; however, from a mechanical point of view, the combined Nb+Ti microalloying concept can be regarded as the more favorable compromise. To interpret the scatter observed in the mechanical properties, OES investigations were carried out. The OES results showed that the chemical composition of the investigated heats can be considered homogeneous with respect to the microalloying elements. Only differences in the range of thousandths of a weight percent were detected in the Nb and/or Ti contents between the individual coils; therefore, the inhomogeneity observed in the mechanical properties cannot be simply attributed to an uneven distribution of the microalloying elements.

SEM investigation showed the presence of Ca–Al–O–S complex inclusions in all three alloying concepts. In the Nb-microalloyed material, MnS inclusions were also observed; however, no Nb-containing precipitates were detected. In the Ti-microalloyed samples, TiN precipitates were observed, and Ti was detected at the outer boundary of the complex inclusions; in addition, MnS inclusions were also present in smaller amounts. In the combined Nb+Ti microalloyed material, both Ti and Nb were detected at the outer boundary of the complex inclusions, while a high number of TiN-based precipitates containing niobium were observed. In this alloying concept, MnS inclusions were not detected. Representative SEM images of the combined Nb+Ti microalloyed sample are shown in **Figure 5**, where **Figure 5a** presents a complex inclusion and **Figure 5b** shows precipitates. The EDS compositions measured at the marked points of the complex inclusion in **Figure 5a** are summarized in **Table 2**, while the point EDS results measured on the precipitates marked in **Figure 5b** are listed in **Table 3**.



Figure 5 Representative SEM image of the combined Nb+Ti microalloyed S355MC steel showing a complex inclusion (a) and precipitates (b)

Table 2 EDS composition measured at the marked points of the complex inclusion shown in Figure 5a for the combined Nb+Ti microalloyed sample (wt.%)

Point	C	O	Mg	Al	S	Ca	Ti	Mn	Fe	Nb
pt1	2.51	11.06	0.34	10.01	0.23	2.93	24.33	–	46.96	1.64
pt2	3.18	40.23	2.00	29.52	0.54	20.42	0.47	–	3.64	–
pt3	5.29	–	–	1.94	26.71	31.56	–	0.92	33.58	–

Table 3 EDS composition measured at the precipitates marked in Figure 5b of the combined Nb+Ti microalloyed sample (wt.%)

Point	C	N	Si	Ti	Cr	Mn	Fe	Nb
pt1	9.99	14.90	–	35.52	–	–	30.72	15.87
pt2	2.61	11.30	–	23.14	–	0.82	55.25	6.87
pt3	2.42	12.66	0.15	21.26	0.30	1.01	55.67	6.53
pt4	2.83	25.50	–	40.18	–	0.62	18.51	12.36

However, the separate inclusion assessment did not confirm a clear and consistent relationship between inclusion content and the measured mechanical properties.

The cost analysis showed that, within the investigated period, the procurement price of FeTi wire was significantly more favorable than that of FeNb wire. According to the collected data, the price difference between the two microalloying wires was approximately fivefold; therefore, a considerable cost reduction may still be achieved even if replacement of a given amount of niobium requires at least twice as much titanium. The cost comparison of the investigated industrial heats is presented in **Figure 6**. The fully Ti-microalloyed heat showed a clearly lower microalloying cost; however, due to the observed mechanical inhomogeneity, this route cannot yet be regarded as a direct industrial substitute in its present form. In the present investigation, the combined Nb+Ti microalloying concept provided more favorable mechanical and metallurgical results, but its economic competitiveness can only be improved significantly by further reducing the Nb content.

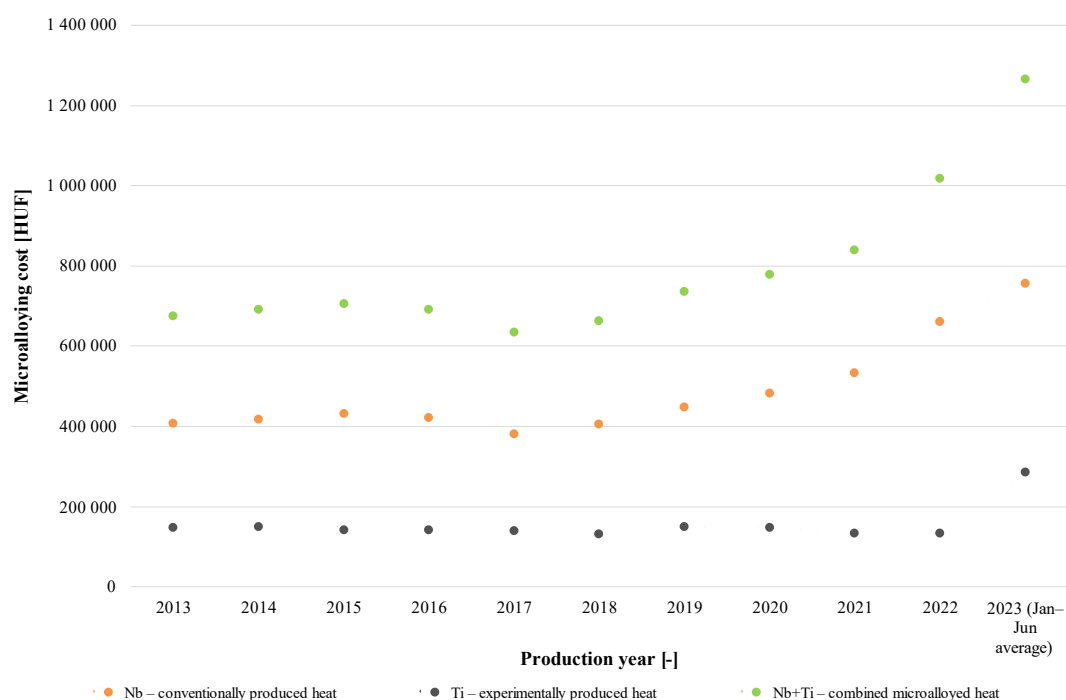


Figure 6 Comparison of the microalloying costs of the investigated heats

4. CONCLUSION

The following conclusions can be drawn from the present work:

- 1) Nb-microalloyed S355MC steel provided the most stable mechanical behavior.
- 2) Ti-microalloyed steel showed lower and more inhomogeneous properties but still fulfilled the relevant standard requirements.
- 3) Combined Nb+Ti microalloying provided a favorable compromise, since the standard mechanical properties were achieved with lower inhomogeneity than in the fully Ti-microalloyed variant.
- 4) OES analysis did not reveal significant chemical inhomogeneity; therefore, the mechanical scatter cannot be attributed solely to the distribution of the microalloying elements.
- 5) SEM investigation showed clear metallurgical differences in Ti-containing systems, especially TiN precipitates and the appearance of Ti and/or Nb at the boundaries of complex inclusions.
- 6) From the economic point of view, Ti-based microalloying is promising, but direct industrial replacement requires further optimization.

Overall, it can be concluded that fully Ti-based substitution is economically promising, but it still requires further optimization from both mechanical and metallurgical points of view. Based on the results of the present investigation, combined Nb+Ti microalloying can be regarded as a more favorable basis for further development.

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