Mourujärvi, Juho; Tihinen, Sakari; Mehtonen, Saara; Lahtinen, Teemu; Santos Vilaca da Silva, Pedro; Kaijalainen, Antti; Porter, David; Kömi, Jukka

Effect of titanium on the weldability of thermomechanically rolled high-strength cold-formable steels

Published in:
METAL 2017 - 26th International Conference on Metallurgy and Materials, Conference Proceedings

Published: 01/01/2017

Document Version
Peer-reviewed accepted author manuscript, also known as Final accepted manuscript or Post-print

Please cite the original version:
Mourujärvi, J., Tihinen, S., Mehtonen, S., Lahtinen, T., Santos Vilaca da Silva, P., Kaijalainen, A., Porter, D., & Kömi, J. (2017). Effect of titanium on the weldability of thermomechanically rolled high-strength cold-formable steels. In *METAL 2017 - 26th International Conference on Metallurgy and Materials, Conference Proceedings* (Vol. 2017-January, pp. 936-941). TANGER Ltd..
https://research.aalto.fi/files/17218009/METAL_2017_Final_Mourujarvi.pdf

EFFECT OF TITANIUM ON THE WELDABILITY OF THERMOMECHANICALLY ROLLED HIGH-STRENGTH COLD-FORMABLE STEELS

MOURUJÄRVI Juho[1], TIHINEN Sakari[2], MEHTONEN Saara[2], LAHTINEN Teemu[3], VILACA Pedro[3], KAIJALAINEN Antti[1], PORTER David[1], KÖMI Jukka[1]

[1]*Materials and Production Engineering – University of Oulu, Finland, EU*
[2]*SSAB Europe Oy, Raahe, Finland, EU*
[3]*Aalto University, Helsinki, Finland, EU*

Abstract

This research is concerned with the effect of titanium in the range 0.01 to 0.13 wt.% on the base plate and weldability properties of laboratory hot-rolled cold-formable steels with yield strengths in the range 500 – 900 MPa (S500MC - S900MC). Different strength levels were achieved by varying the contents of boron, chromium, molybdenum and manganese. For the base metal, titanium had a small strengthening effect and it also raised the impact transition temperature. In MAG-welding ($t_{8/5}$ = 5 s), titanium had a strengthening effect probably due to precipitation strengthening which was seen both in the strength of the welded steels and in the lower hardness difference between the base metal and the HAZ. Titanium, especially with higher concentrations, had a clear negative effect on the impact toughness of the fusion line and a somewhat smaller negative effect on the impact toughness of the fusion line + 1 mm position. This was probably due to the presence of large angular TiN inclusions promoting cleavage crack nucleation. Also unlike TiN precipitates, these inclusions are ineffective in preventing austenite grain coarsening in the coarse-grained HAZ (CGHAZ).

Overall, high titanium contents have been shown to have a detrimental effect on HAZ properties: although titanium reduces the softening of the HAZ experienced in these types of steels, it has a clear negative effect on the HAZ impact toughness with low heat input.

Keywords: high strength steel, weldability, HAZ, titanium, Ti/N ratio

1. INTRODUCTION

In this research the effect of titanium on the weldability of thermomechanically rolled high-strength cold-formable steels is investigated. High concentrations of titanium have been usually used in production process of these steels due to precipitation hardening of titanium. Precipitation hardening is a part of thermomechanical rolling process, where steel strip is coiled in about 600°C. According to previous researches, high concentrations of titanium can deteriorate the toughness of HAZ due to high Ti/N ratio that causes large angular TiN inclusions promoting cleveage crack nucleation. These inclusions, unlike TiN precipitates, are also ineffective in preventing austenite grain coarsening in the CGHAZ. Instead of preventing grain coarsening, titanium has been noted to have strengthening effect promoting coarse upper bainite microstructure to the fusion line and next to the fusion line in the CGHAZ. This effect is stronger with low heat inputs when microstructure has no time to get normalized. This is problem, because when matching weld is requirement, heat input must be enough low. Brittle microstructure with large grain size cause poor toughness and fatigue to these high titanium alloyed steels, even though welding process is carried out with recommendations.

Therefore the effect of different concentrations of titanium are researched to achieve better HAZ toughness to hot-rolled cold-formable steels with yield strengths in the range 500 – 900 MPa. The purpose of this research is to find out if smaller titanium concentrations are key to better toughness properties to these steels.

In this research are 11 different experimental steels, which have different contents of titanium and also boron, chromium, molybdenum and manganese giving these steels different strength levels (500 – 900 MPa). Mechanical testing is carried out for base metals and welded metals. MAG weldings are carried out with 5 s $t_{8/5}$ -time. Some microstructure pictures are also taken to get more information from the results.

2. EXPERIMENTAL

2.1. Investigated steels

For investigating the effect of titanium, 11 laboratory slabs were produced for laboratory rolling process. First, slabs were cut into blocks and heated in an oven for about two hours in 1200 °C temperature. Six rolling passes were used to roll these 55 mm thick blocks to achieve the final thickness of about 8 mm and immediately after rolling the plates were submerged to water for simulating direct quenching.

Chemical compositions of the experimental steels are shown in Table 1. Titanium contents are in the range 0.01 to 0.13 wt.% and different strength levels were achieved by varying the contents of boron, chromium, molybdenum and manganese to see the effect of titanium in different strength levels. All the steels form comparable couples with each other. The rest three steels in Table 1 are so called additional steels, which are from the Master's thesis of Teemu Lahtinen (x). Steels are produced in the same way and were taken into this research to get comparable steel compositions also with low titanium content.

Table 1 Chemical compositions of the experimental steels (in wt.%)

Steel	C	Si	Mn	Al	Nb	Mo	Cr	Ti	B	N
0.5Cr0.04TiB	0.07	0.2	1.3	0.04	0.08	0	0.5	0.04	0.0025	0.004
0.5CrB	0.07	0.2	1.3	0.04	0.08	0	0.5	0	0.0030	0.004
0.5Cr0.04Ti	0.07	0.2	1.3	0.03	0.08	0	0.5	0.04	0	0.003
0	0.07	0.2	1.3	0.03	0.08	0	0	0	0	0.003
0.13Ti	0.07	0.2	1.3	0.03	0.09	0	0	0.13	0	0.004
0.25Cr0.05Ti	0.07	0.2	1.3	0.03	0.08	0	0.25	0.05	0	0.003
0.5Cr	0.07	0.2	1.3	0.02	0.08	0	0.5	0	0	0.004
0.5Cr0.11Ti	0.07	0.2	1.3	0.03	0.08	0	0.5	0.11	0	0.004
0.7Cr0.01TiB	0.07	0.2	1.3	0.03	0.08	0	0.7	0.01	0.002	0.005
0.5Cr0.01TiMoB	0.07	0.2	1.3	0.03	0.08	0.2	0.5	0.01	0.002	0.005
0.5Cr0.01TiMnB	0.06	0.2	1.5	0.03	0.08	0	0.5	0.01	0.002	0.006

2.2. Mechanical testing

Tensile tests were carried out at room temperature in accordance with the European standard EN 10002 using flat specimens (6 x 20 x 120 mm^3). Base metal tests were along the rolling direction except for the additional steels, which were in transversal direction. All tensile tests of the welds were in transversal direction. All tensile tests included 2 specimens per steel. Charpy-V impact testing was performed in accordance with the European standard EN 10045 at various temperatures (2 specimens / temperature), ranging from 60 °C to -160 °C using subsize specimens 5 x 10 x 55 mm^3. For base metal tests were taken along both the rolling and transverse directions and for the weld samples notches were placed at the fusion line and fusion line + 1 mm. Hardness measurements were carried out for specimens using HV10 technique.

2.3. Welding

Welding method was MAG welding, used shielding gas MISON 8 (Ar + 8 % CO2 + 0,03 % NO) (aga 2012) and the filler metal was Böhler X70 IG (böhler welding group). Welding joint types were V-grooves and the welding processes were done with two runs.

2.4. Microstructural characterization

General microstructure characterization was done using JEOL JSM-7000F FESEM. Specimens for microstructure examination were done by mounting the steel pieces and then polishing and etching the surfaces. Used etchant was 4 % Nital which is 96 % ethanol and 4 % nitric acid.

3. RESULTS AND DISCUSSION

3.1. Base metal results

The mechanical properties of the base metals are presented in Table 2. Yield strengths were in the range 500 – 900 MPa and all the 5 boron-alloyed steels were in their own strength level near 900 MPa. Boron is known for enhancing the hardenability of steel remarkably due to precipitation of free boron to the austenite grain boundaries preventing the nucleation of grain boundary ferrite and promoting the formation of pre-eutectic ferrite inside the grains affecting significant fining of microstructure and higher hardenability. Although this effect is achieved only if boron is in soluble form without carbides or nitrides and is protected with higher affinite alloying elements to nitrogen, like with these steels, alloying titanium or aluminium. (1). Chromium and molybdenum affected also significantly to the strengths by increasing it. The strengthening effect of both of these alloying elements is based on enhancing the hardenability by slowing the diffusion of austenite (1)(2).

The effect of titanium to the base metal strength seemed to be small. The strengthening effect of titanium was the more effective, the less the steel had hardenability enhancing alloying elements like boron or chromium. In steels without chromium titanium increased the strength.

Table 2 Base metal mechanical properties

Steel	Rp0.2 (MPa) longitudinal	Rm (MPa) longitudinal	A (%) longitudinal	CV -40 °C (J) transversal	CV -60 °C (J) transversal	T_{14J} (°C) transversal
0.5CrB	898	1140	13.5	27	25	-113
0.5Cr0.04TiB	864	1095	13.0	31	26	-96
0.5Cr0.04Ti	639	893	17.3	38	34	-116
0.5Cr	615	876	17.6	43	41	-132
0.5Cr0.11Ti	602	843	17.9	45	47	-110
0.25Cr0.05Ti	588	829	18.5	50	48	-117
0.13Ti	546	755	23.1	60	59	-125
0	515	781	19.8	55	57	-132
Additional steel	Rp0.2 (MPa) transversal	Rm (MPa) transversal	A (%) transversal	CV -40 (J) transversal	CV -60 (J) transversal	
0.5Cr0.01TiMoB	904	1126	7.4	29	27	-
0.7Cr0.01TiB	894	1112	8.1	30	26	-
0.5Cr0.01TiMnB	864	1050	5.5	30	27	-

Transition temperatures were defined for all the steels except the additional steels. The results are shown in transversal direction to be better compared to the welding results. Transition temperatures were between -96 °C and -132 °C (Figure 1) and are seen at the Table 2. The large strength range didn't seem to affect to the T_{14J} –values but steels with higher strength seemed to have lower impact values at -40 °C and -60 °C. T_{14J} –values showed that titanium raised the transition temperatures. The effect can be seen from the Table 2 comparing the 0.5Cr wt.% -steels. Titanium raised the temperatures probably because of large angular titanium nitrides (TiN), which promote cleavage crack nucleation. In the figure 1 can be seen large TiN inclusions in the base metal of steel 0.13Ti.

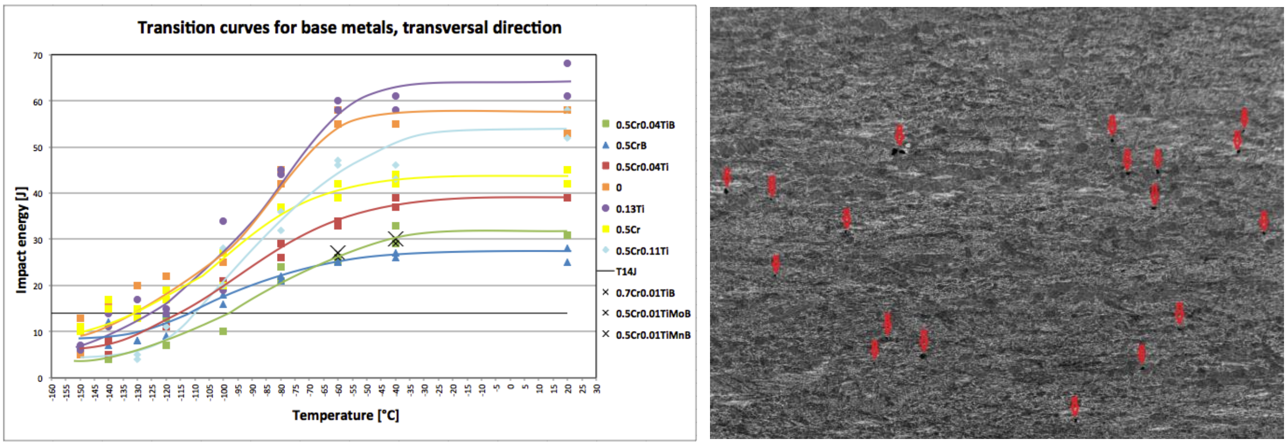

Figure 1 Transversal transition curves for base metals and TiN inclusions in the base metal of steel 0.13Ti

3.2. MAG-welding results

The mechanical properties after welding are presented in Table 3. From the hardness results can be seen that titanium had some kind of strengthening effect, which is probably due to precipitation strengthening. The effect can be seen when comparing for example the hardness differences of 0 vs. 0.13Ti and 0.5CrB vs. 0.5Cr0.04TiB steels. The elongation values are also highest with high titanium-alloyed steels.

Table 3 Mechanical properties after welding (transversal)

Steel	Rp0.2 (MPa)	Rm (MPa)	A (%)	BM (HV)	ICHAZ (HV)	BM -> ICHAZ	Ti/N	FL T_{14J} (°C)	FL -40 °C (J)	FL -60 °C (J)	FL + 1mm T_{14J} (°C)
0.5Cr0.01TiMnB	783	891	4.8	365	230	-135	1.8	-	38	16	-
0.5Cr	689	824	6.8	290	220	-70	0.0	-70	31	26	-120
0.5CrB	828	939	4.4	370	240	-130	0.0	-70	28	19	-83
0	631	767	8.6	250	210	-40	0.0	-72	27	19	-116
0.7Cr0.01TiB	792	906	4.3	365	220	-145	2.0	-	22	22	-
0.5Cr0.01TiMoB	810	914	4.9	360	260	-100	1.9	-	16	12	-
0.5Cr0.04Ti	713	855	6.3	295	230	-65	12.6	-28	15	7	-100
0.5Cr0.04TiB	875	967	5.4	370	250	-120	12.1	-28	14	9	-83
0.25Cr0.05Ti	673	812	7.2	270	220	-50	15.6	-35	14	12	-95
0.13Ti	646	788	12.2	240	220	-20	38.0	-17	10	8	-102
0.5Cr0.11Ti	677	821	10.9	250	220	-30	29.7	-17	9	8	-95

After welding the variation in strengths was large like it was in base metals. Yield strengths were in the range 630 – 875 MPa and tensile strengths in the range 770 – 970 MPa. Therefore matching weld were achieved and 5 s $t_{8/5}$ –time hadn't decreased the strengths. However direct comparing can't be done between the base metal strength and the strength after welding because the base metal results are mainly in longitudinal direction and the welding results are in transversal direction. However when comparing the strength order of the steels between the base metal and the MAG-welds it can be seen that it's almost the same except the steel with the highest strength, which is 0.5Cr0.04TiB in welding results, and 0.5CrB in base metal results. Again, titanium has probably had a strengthening effect due to precipitation strengthening when welding steels. Also 0.13Ti –steel has higher tensile strength than 0 –steel after welding and moreover when comparing the 0.5Cr –steels it can be seen that the tensile strength of 0.5Cr0.11Ti has lowered least.

After the excellent impact toughness results of base metals, the same can't be stated for the MAG-welding impact toughness results. T_{14J} transition temperatures were still in good level in the fusion line + 1 mm but in the fusion line the temperatures increased significantly. In the fusion line + 1 mm the temperatures had raised about 12 – 30 °C and in the fusion line about 45 – 110 °C when comparing them to the base metal transversal T_{14J} results. T_{14J} transition temperatures were in fusion line + 1 mm -83 - -120 °C and in fusion line -17 - -72 °C. Impact toughness results decreased significantly in fusion line which is the weakest area in weld. From the Table 3 can be seen that the large strength range didn't affect to the T_{14J} transition temperatures in the fusion line.

Therefore the most effective factor decreasing the impact toughness was titanium. When the titanium concentration was higher also the T_{14J} transition temperatures were higher. The effect of titanium in fusion line was significant because when comparing high titanium-alloyed steel, with or without chromium content, T_{14J} transition temperature was about 55 °C higher with high titanium-alloyed steel. The previous researches have also noted deteriorate effect of titanium to the impact toughness of HAZ (Chang et al. 2002, Doi et al. 2000, Rak et al. 1997, Wang et al. 1991).

High titanium contents mean high Ti/N –ratios and therefore titanium nitrides have grown to large inclusions, which don't prevent the grain growth anymore because of losing the pinning effect. Additionally these large TiN inclusions promote cleavage crack nucleation decreasing the toughness of steel. In the Figure 2 are shown the Ti/N ratios compared to T_{14J} transition temperatures in fusion line and Ti/N ratios compared to fusion line impact energies at -40 °C. These figures confirm this negative effect of titanium to the toughness.

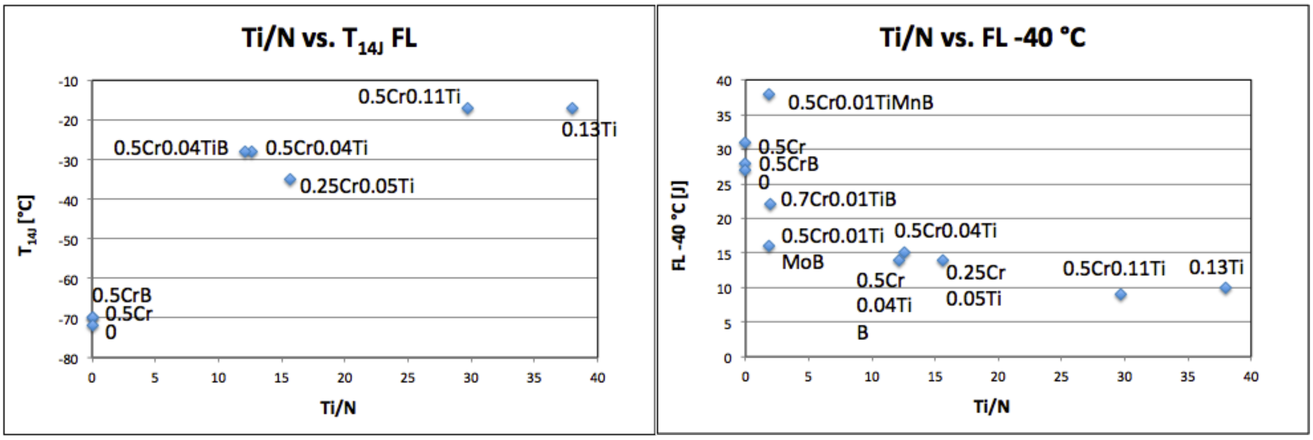

Figure 2 Ti/N ratios compared to T_{14J} transition temperatures in fusion line and Ti/N ratios compared to fusion line impact energies at -40 °C

Because the stoichiometric ratio for titanium and nitrogen is 3.42, it can be noted that these fusion line weak steels in this research have notably high Ti/N ratios. To get ideal stoichiometric Ti/N ratio with usual 30 - 40 ppm nitrogen levels, steels should have about 0.015 wt.% titanium content. On the other hand the most optimal Ti/N ratio would be a bit below 3.42 because steels contain normally also other nitrogen bonding alloying elements like boron and aluminium. The titanium content of the additional steels is about 0.01 wt.% and the Ti/N ratios of these steels are about 2.0 or a bit lower. It can be seen from the Table 3 and the Figure 2 that the fusion line impact energies of these steels are better than the steels with higher titanium content. It has been stated that with lower titanium content less large TiN inclusions and more small TiN precipitations are formed which is beneficial to the impact toughness (Harrison 1997). In that case also Ti/N ratio is closer to the ideal 3.42 value and therefore the effect of titanium preventing grain growth would be better in CGHAZ next to fusion line (Medina et al. 1999).

0.5Cr0.01TiMoB –steel have the lowest impact energies of the additional steels and the values are only a little higher than the values of high titanium-alloyed steels (≥ 0.04 wt.%). The reason is 0,20 wt.% molybdenum content of that steel which was added for trying to maintain the strength and hardness in the HAZ because the strength and resistance for softening during welding was assumed to be improved by molybdenum alloying. Adding molybdenum has been shown to increase the strength considerably and at the same time the toughness of both base material and HAZ may deteriorate (16). 0.5Cr0.01TiMoB –steel had the highest yield strength (904 MPa) of the steels in this research, even though it’s a transversal value.

4. CONCLUSION

In this paper the effect of titanium on the weldability of thermomechanically rolled high-strength cold-formable steels have been investigated. High titanium contents have been shown to have a detrimental effect on HAZ properties: although titanium reduces the softening of the HAZ, it has a clear negative effect on the HAZ impact toughness with low heat input. For the base metal, titanium had a small strengthening effect but it also raised the impact transition temperature. In MAG-welding ($t_{8/5}$ = 5 s), titanium had a strengthening effect probably due to precipitation strengthening which was seen both in the strength of the welded steels and in the lower hardness difference between the base metal and the HAZ. Titanium has a clear negative effect on the HAZ impact toughness with low heat input probably due to the presence of large angular TiN inclusions, which promote also cleavage crack nucleation. Also unlike fine TiN precipitates, these large inclusions are ineffective in preventing austenite grain coarsening in the coarse-grained HAZ.

ACKNOWLEDGEMENTS

Financial support from Tekes (Finnish Funding Agency for Technology and Innovation) and SSAB Europe Oy is gratefully acknowledged. A part of this research was carried out under the auspices of Digital, Internet, Materials & Engineering Co-Creation, DIMECC Oy.

REFERENCES

Examples are shown for: [1] - a book, [2] - article in a journal, [3] - paper in the proceedings:

[1] COOK, C. J., KERSE, C. S. *Merger control. 3rd ed.* London: Sweet & Maxwell, 2000. 376 p.

[2] VAN DER VET, P. E., MARS, N.J. Condocet querry engine*. Journal of the American Society for information science*, 1999, vol. 42, no. 6, pp. 485-492.

[3] SMEJKAL, V. FEM modeling and experimental research of through-thickness strain distribution during hot plate rolling. In *METAL 2014: 23rd International Conference on Metallurgy and Materials*. Ostrava: TANGER, 2014, pp. 289-294.

[4] (1) Lindroos et al. 1986

[5] (2) R. D. Stout, Welding Research Council, 1987