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

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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 small TiN particles precipitated from the solid state, 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 has been investigated. High concentrations of titanium have usually been used in the production of these steels due to titanium carbide precipitation hardening associated with strip is coiling at about 600 °C. According to previous research [1-6], high concentrations of titanium can deteriorate the toughness of the HAZ due to high Ti/N ratios causing the formation of large angular TiN inclusions that promote cleavage crack nucleation. These inclusions, unlike TiN precipitates, are also ineffective in preventing austenite grain coarsening in the CGHAZ, which is also detrimental to HAZ toughness and fatigue properties. However, titanium has a strengthening effect by promoting upper bainite at the fusion line and in the CGHAZ, especially with low heat inputs. This is beneficial when matching welds are required especially in the case of the lean thermos-mechanically rolled and direct quenched steels that have been studied here. Therefore, the purpose of the present work was to study the effects of different concentrations of titanium in hot-rolled cold-formable direct quenched steels with the aim of being able to find an optimum balance between the beneficial effects of titanium on strength and the detrimental effects on HAZ toughness. The yield strength range concerned was 500 - 900 MPa. 11 different experimental steels having different contents of titanium, boron, chromium, molybdenum and manganese were MAG welded with a 5 s $t_{8/5}$ cooling time and the mechanical properties and microstructures of the welds were determined.

2. EXPERIMENTAL

2.1. Investigated steels

The chemical compositions of the 11 laboratory vacuum castings are given in **Table 1**. The titanium contents are in the range 0.01 to 0.13 wt. %. In addition the contents of boron, chromium, molybdenum and manganese were varied to reveal the effect of titanium in base metals with different strength levels. All the steels form comparable couples with each other to reveal the effects of different combinations of titanium and other alloying elements. The last three steels in **Table 1** are additional steels from the Master's thesis of Lahtinen [7]. They are all low-titanium compositions for general comparison.

The cast slabs (55 x 300 x 450) mm were cut into (55 mm thick x 75 x 150) mm blocks and heated for two hours to 1200 °C. Six rolling passes with final rolling temperature of 850 °C were used to roll the blocks to the final thickness of 8 mm followed by immediate submerging in a water tank to simulate direct quenching.

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

Steel	C	Si	Mn	Al	Nb	Mo	Cr	Ti	B	N
0.5CrB	0.07	0.2	1.3	0.04	0.08	0	0.5	0	0.0030	0.004
0.5Cr0.04TiB	0.07	0.2	1.3	0.04	0.08	0	0.5	0.04	0.0025	0.004
0.5Cr0.04Ti	0.07	0.2	1.3	0.03	0.08	0	0.5	0.04	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
0.25Cr0.05Ti	0.07	0.2	1.3	0.03	0.08	0	0.25	0.05	0	0.003
0.13Ti	0.07	0.2	1.3	0.03	0.09	0	0	0.13	0	0.003
0	0.07	0.2	1.3	0.03	0.08	0	0	0	0	0.003
0.7Cr0.01TiB	0.07	0.2	1.3	0.03	0.08	0	0.7	0.01	0.0020	0.005
0.5Cr0.01TiMoB	0.07	0.2	1.3	0.03	0.08	0.2	0.5	0.01	0.0020	0.005
0.5Cr0.01TiMnB	0.06	0.2	1.5	0.03	0.08	0	0.5	0.01	0.0020	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 test specimens were in the rolling direction except for the last three steels in **Table 1**, which were in the transverse direction. Cross-weld tensile tests were transverse to the rolling direction due to the orientation of the welds. 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 20 °C to -150 °C using subsize specimens 5 x 10 x 55 mm^3. For the base metals, transverse specimens were tested and for the weld samples notches were placed at the fusion line and fusion line + 1 mm. Vickers hardness measurements were made in the base metal and HAZ using a 10 kg load.

2.3. Welding

X 70-IG [8, 9]. Two weld runs were deposited into V preparations.

2.4. Microstructural characterization

General microstructure characterization was done using a JEOL JSM-7000F FESEM with specimens etched in MAG welding was made using the shielding gas MISON 8 (Ar + 8 % CO_2 + 0.03 % NO) and the filler metal Böhler 4 % Nital, i.e. 96 % ethanol and 4 % nitric acid.

3. RESULTS AND DISCUSSION

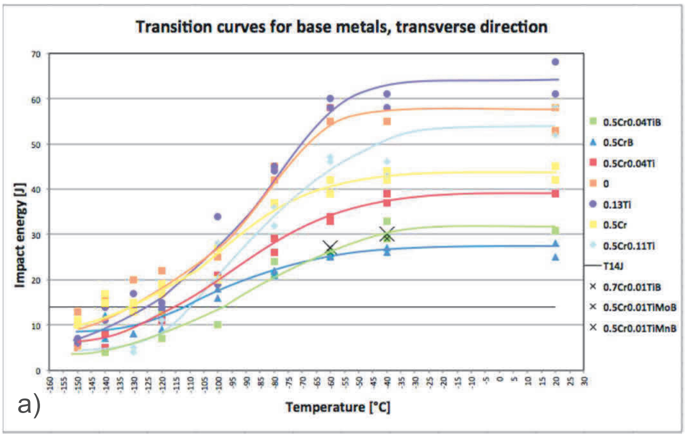
3.1. Base metal properties

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. Provided it is protected from forming boron nitride by the presence of a strong nitride former like titanium, boron enhances the hardenability of steel by segregating to the austenite grain boundaries and thereby preventing the nucleation of pro-eutectoid ferrite leading to the formation of finer lower transformation temperature microstructural components like bainite and martensite [10, 11]. Chromium and molybdenum also led to significant strengthening through increased hardenability [11, 12]. The effect of titanium on the base metal strength seems to be small. However, the strengthening effect of titanium is somewhat greater when other hardenability enhancing alloying elements like boron or chromium are at low levels.

Table 2 Base metal mechanical properties

Steel	$R_p0.2$ (MPa) longitudinal	R_m (MPa) longitudinal	A (%) longitudinal	CV -40 °C (J) transverse	CV -60 °C (J) transverse	T_{14J} (°C) transverse	Upper shelf energy (J) transverse
0.5CrB	898	1140	13.5	27	25	-113	29
0.5Cr0.04TiB	864	1095	13.0	31	26	-96	31
0.5Cr0.04Ti	639	893	17.3	38	34	-116	39
0.5Cr	615	876	17.6	43	41	-132	43
0.5Cr0.11Ti	602	843	17.9	45	47	-110	52
0.25Cr0.05Ti	588	829	18.5	50	48	-117	51
0.13Ti	546	755	23.1	60	59	-125	62
0	515	781	19.8	55	57	-132	58
Additional steel	$R_p0.2$ (MPa) transverse	R_m (MPa) transverse	A (%) transverse	CV -40 °C (J) transverse	CV -60 °C (J) transverse		
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	-	-

Charpy V transition curves for all but the additional base metals are shown in **Figure 1a**. **Table 2** shows transition temperatures corresponding to 14 J absorbed energy (T_{14J}), which is appropriate for the sub-sized 5 mm thick specimens concerned. Transition temperatures were between -96 °C and -132 °C. The large range of strengths involved did not seem to affect T_{14J} but, as expected, steels with higher strength had lower upper shelf energies, which was also reflected in the impact values at -40 °C and -60 °C. Comparing the values of T_{14J} for the first five 0.5Cr compositions in **Table 2** shows that titanium raises the transition temperatures. This is presumably due to the presence of large angular titanium nitrides, which promote cleavage crack nucleation, see e.g. **Figure 1b**, where large TiN inclusions in the base metal of steel 0.13Ti are arrowed.



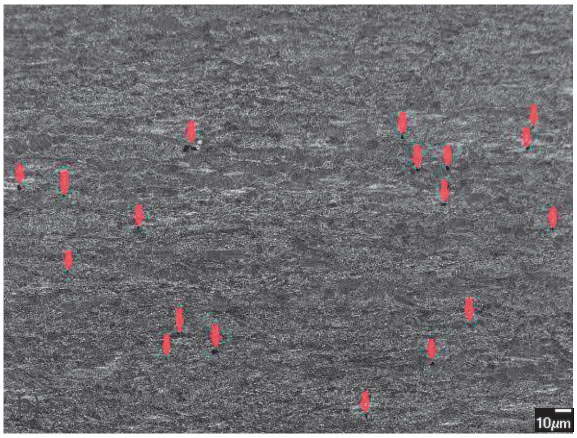


Figure 1 a) Base metal transverse transition curves b) TiN inclusions in the base metal of steel 0.13Ti

3.2. MAG welding results

The mechanical properties of the welded joints are presented in **Table 3**. After welding the lowest hardness values are found in the ICHAZ, therefore these are included for comparison with the base plate. By comparing, for example, the hardness differences of steel 0 vs. 0.13Ti and steel 0.5CrB vs. 0.5Cr0.04TiB, it can be seen that titanium additions result in strengthening of the ICHAZ, presumably due to precipitation strengthening. This is also reflected in the elongation to fracture values of the cross-weld tensile tests, which are highest for the high-titanium steels.

Table 3 Mechanical properties of welded joints (transverse)

Steel	R_p0.2 (MPa)	R_m (MPa)	A (%)	BM (HV)	ICHAZ (HV)	BM (HV) -> ICHAZ (HV)	Ti/N	FL T_{14J} (°C)	FL -40 °C (J)	FL -60 °C (J)	FL + 1mm T_{14J} (°C)
0.5CrB	828	939	4.4	370	240	-130	0.0	-70	28	19	-83
0.5Cr0.04TiB	875	967	5.4	370	250	-120	12.1	-28	14	9	-83
0.5Cr0.04Ti	713	855	6.3	295	230	-65	12.6	-28	15	7	-100
0.5Cr	689	824	6.8	290	220	-70	0.0	-70	31	26	-120
0.5Cr0.11Ti	677	821	10.9	250	220	-30	29.7	-17	9	8	-95
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	631	767	8.6	250	210	-40	0.0	-72	27	19	-116
Additional steel											
0.5Cr0.01TiMoB	810	914	4.9	360	260	-100	1.9	-	16	12	-
0.7Cr0.01TiB	792	906	4.3	365	220	-145	2.0	-	22	22	-
0.5Cr0.01TiMnB	783	891	4.8	365	230	-135	1.8	-	38	16	-

Regarding the cross-weld strength properties, the variation in strengths is again large as it is with the base metals. Yield strengths are in the range 630 - 875 MPa and tensile strengths in the range 770 - 970 MPa. Direct comparison between the base metal strength and the strength after welding is not possible because the base metal was tested with mainly longitudinal specimens while the cross-weld specimens were transverse to the rolling direction. When comparing the order of the steels with regard to the strengths of the base metals and the MAG welds, it can be seen that they are almost the same except for the steels with the highest strengths, which is 0.5Cr0.04TiB after welding and 0.5CrB for the base metals. Again, titanium has probably had a strengthening effect due to precipitation strengthening in the welds. This can be seen from the fact that steel 0.13Ti has a higher cross-weld tensile strength than steel 0 and moreover when comparing all the steels with 0.5Cr, it can be seen that the tensile strength of that with the highest titanium content, 0.5Cr0.11Ti, has decreased the least.

Impact toughness results showed that the fusion line is the weakest area in the weld. T_{14J} transition temperatures were at a good level in the fusion line + 1 mm position, but in the fusion line T_{14J} increased significantly. Compared to the base metal transverse T_{14J} results, in the fusion line + 1 mm, T_{14J} increased by about 12 - 30 °C and in the fusion line by about 45 - 110 °C. T_{14J} transition temperatures were in fusion line + 1 mm -83 - -120 °C and in fusion line -17 - -72 °C.

From **Table 3** it can be seen that the large strength range did not affect T_{14J} in the fusion line. However, there is a clear correlation between the titanium concentration and T_{14J}: when comparing the high-titanium steels, with or without chromium, T_{14J} values were about 55 °C higher in the case of the high titanium content.

High titanium contents imply high Ti/N ratios which mean that titanium nitride precipitates tend to grow in the CGHAZ and not prevent grain growth because of the loss of grain boundary pinning. The high Ti contents together with the 0.003 - 0.006 wt. % of N mean that the steels additionally contain large TiN inclusions that promote cleavage crack nucleation and decrease the toughness of steel. **Figure 2**, showing fusion line T_{14J} transition temperatures and impact energies at -40 °C vs. Ti/N ratios illustrates the negative effect of titanium on toughness.

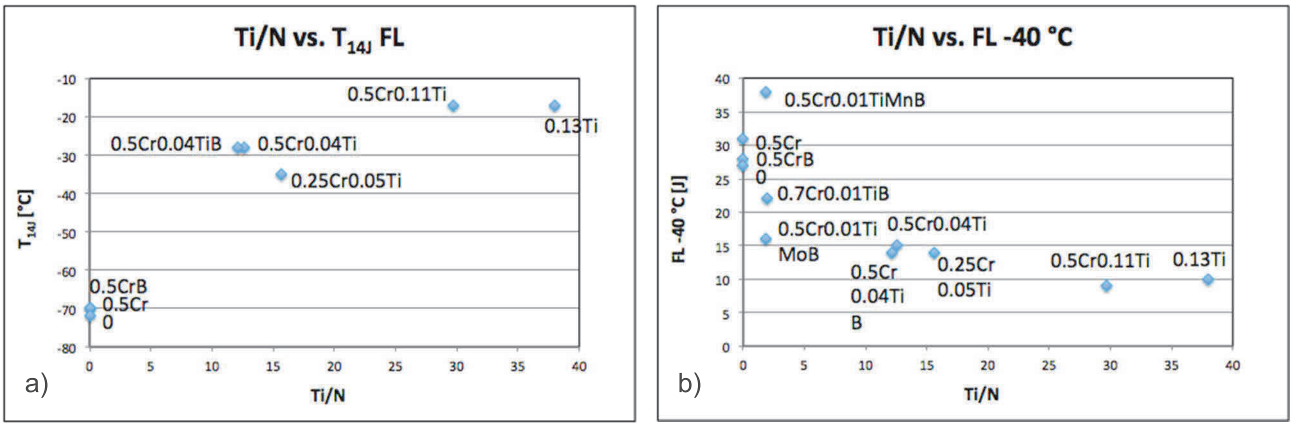


Figure 2 a) T_{14J} transition temperatures in fusion line vs. Ti/N ratios (excluding the additional steels for which data is not available) b) Fusion line impact energies at -40 °C vs. Ti/N ratios for all the steels

It can be seen that the steels with low fusion line toughness have notably high Ti/N ratios compared to the stoichiometric ratio 3.42. Considering the restriction of grain growth in the CGHAZ, the optimum Ti/N ratio is less than stoichiometric [2], which, for 30 - 40 ppm nitrogen levels, corresponds to less than of about 0.015 wt. % of titanium. The titanium content of the additional steels is about 0.01 wt. % giving Ti/N ratios of 2.0 or less. It can be seen from the **Table 3** and **Figure 2b** 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 fewer large TiN inclusions are present (due to lower products Ti x N) and more small stable TiN precipitates are present which is beneficial to the restriction of grain growth. Both factors are beneficial with respect to the impact toughness of the CGHAZ [1]. 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 the CGHAZ next to fusion line [13].

Steel 0.5Cr0.01TiMoB has the lowest impact energies of the additional steels. Despite its low (0.01 wt. %) titanium its toughness at -40 °C is only slightly higher than that of the higher titanium steels with 0.04 wt.% Ti or more. The reason for this may be the presence of 0.20 wt. % molybdenum that was added to the steel in order to better maintain the strength and hardness in the HAZ. 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 [12]. Indeed, steel 0.5Cr0.01TiMoB had the highest yield strength of the studied steels.

4. CONCLUSIONS

The effect of titanium on the weldability of thermos-mechanically rolled and direct quenched high-strength cold-formable steels has been investigated for a range of chemistries and yield strength levels 515 - 904 MPa. MAG welding was performed such as to produce a cooling time $t_{8/5}$ = 5 s. While high titanium contents were shown to reduce the softening of the HAZ that is common to direct quenched un-tempered steels, contents of 0.04 wt. % or more had a detrimental effect on HAZ and base metal impact toughness. The strengthening effect was 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. The detrimental effect of titanium on the HAZ impact toughness is probably due to the presence of large angular TiN inclusions promoting cleavage crack nucleation. In addition, high additions of titanium lead to Ti/N ratios that promote coarsening of any fine TiN precipitates and more pronounced grain growth in the CGHAZ.

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REFERENCES

[1] HARRISON, P. L., BATESON, P. H. Observations on the Effects of Titanium Treatment on HAZ Microstructure and Toughness. In *Titanium Technology in Microalloyed Steels.* Sheffield: 1994, pp. 180-196.

[2] CHANG, W., YOON, B., BANG, K. Microstructures and Toughness of Simulated HAZ in Quenched and Tempered, Low-carbon, Ti-B Containing Steels. In *6th International Trends in Welding Research Conference Proceedings*. Phoenix: 2002, pp. 742-747.

[3] DOI, M., ENDO, S., OSAWA, K. Effect of Ti Content on TiN Morphology, Microstructure and Toughness in Coarse-grained Heat Affected Zone of Ti-containing Steels. *Welding International*, 2000, vol. 14, no. 4, pp. 281-287.

[4] RAK, I., GLIHA, V., KOCAK, M. Weldability and Toughness Assessment of Ti-Microalloyed Offshore Steel. *Metallurgical and Materials Transactions A*, 1997, vol. 28, no. 1, pp. 199-206.

[5] WANG, S., CHEN, S., HSIEH, R. The Effects of Titanium and Nitrogen Contents on the Austenite Grain Coarsening Behavior and HAZ Toughness of Steel Plates. *China Steel Technical Report*, 1991, no. 5, pp. 1-8.

[6] SAGE, A. The Role of Micro-alloys in Thermomechanically Processed Steels. In *International conference on Physical Metallurgy of Thermomechanical Processing of Steels and Other Materials*. Tokyo: 1988, pp. 11-19.

[7] LAHTINEN, T. Analysis and Development of Weldability of Novel 700 MPa High Strength Steels. *Master's thesis*. Tampere University of Technology, 2016. 140 p.

[8] AGA. MISON Shielding Gases, 2017. http://www.aga.fi/en/products_ren/cutting_welding_gases/shielding_gases/mison_shielding_gases/index.html

[9] BÖHLER WELDING. Böhler X 70-IG Filler Metal, 2017. http://www.vabw-service.com/documents/boehler/datenblaetter/en/B_Boehler%20X%2070-IG_de_en_5.pdf?cache=1479374087

[10] LUDLOW, V., SENK, D., ALVAREZ DE TOLEDO, G., ZAJAC, S., MULLER, K. T. *Precipitation of Nitrides and Carbides During Solidification and Cooling*. European Commission Technical Research, 2006. 303 p.

[11] LINDROOS, V., SULONEN, M., VEISTINEN, M. *Uudistettu Miekk-ojan Metallioppi. 1st ed.* Helsinki: Teknillisten Tieteiden Akatemia Ry, 1986. 841 p.

[12] STOUT, R. D., *Weldability of Steels. 4th ed.* Welding Research Council, 1987. 449 p.

[13] MEDINA, S. F., CHAPA, M., VALLES, P., QUISPE, A., VEGA, M. I. Influence of Ti and N Contents on Austenite Grain Control and Precipitate Size in Structural Steels. *ISIJ International*, 1999, vol. 39, no. 9, pp. 930-936.