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Improving the Strength of Prestressed Steel ASTM A633 Grade C by Combination of the Cr-Ti Alloying and Heat Treatment

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Abstract

Laboratory-scale experiments were carried out to improve the strength of prestressed steel by combination of the Cr-Ti alloying and heat treatment. A predetermined amount of the scrap and some ferrous alloys (such as FeMn, FeSi, FeCr and FeTi) was melted in the induction furnace to obtain the aimed compositions of the steel ASTM A633 grade C and the modified steel with Cr-Ti alloying. The molten steel was cast into the ϕ45 mm ingot which was then hot forged into the ϕ25 mm, subsequently prepared the tensile specimens that were heat-treated by quenching and tempering. After that, the hot forged and heat-treated specimens were subjected to the composition analysis, the tensile test and microstructural observation by optical and scanning electron microscopy. It has been concluded that the strengths of the prestressed steel strongly increased when the martensitic microstructure was obtained through the proper heat treatment. All the prepared steel exhibited high strength and adequate elongation, especially the UTS/YS of the Cr-Ti alloyed steel had increased from the value of 961/702 to 1611/1217 MPa and the elongation decreased from 15 to 10% corresponding to the deformed and heat-treated sample. These increasing strengths were attributed to the hardenability of the Cr element as well as the formation of the TiN precipitates which hindered the movement of the dislocation. The results suggested that further research must be conducted for the practical production of prestressed steel that is used in construction applications.

Keywords: Prestressed steel, Cr-Ti addition, heat treatment, tensile strength, precipitate.

1. Introduction

It is acknowledged that there are many steel strengthening methods that have been successfully applied so far. Among them, alloying addition or/and heat treatment are frequently used. In general, some alloying elements such as Si, Mn, Cr, and others are added to steel to improve its properties. The specific elements and the alloying amount are determined by the application and the economic term, so the degree of increased strength and cost of the alloying elements must be considered carefully. As a result, there are many grades of steel that have been developed so far. For construction, the Si-Mn steel is popular due to having the compromise between the mechanical properties and the production cost. As the total content of the alloying elements is less than 3 wt.%, this grade is known as low alloy steel. Many considerable efforts have been directed towards the production of high strength low alloy (HSLA) steels for construction as skyscraper, bridge, tower, etc. These modified steels which rely on a combination of precipitation of carbides and nitrides, and grain refining for their strengthening mechanism can meet the requirements of a composite set of high strength, good resistance to brittle fracture, low-temperature toughness as well as high degree of weldability [1]. In the construction, the HSLA steel that is used for pre-stressed application requires high strength, adequate ductility, low relaxation to reduce losses and minimum corrosion to raise the resistance to tension of reinforced concrete. Prestressing technique raises both the quality and the resistance to tension and compression characteristics of the steel by creating a state of co-action in which the tension and deformation are opposed to those induced by the loads that will subsequently act upon the structure [2]. The strength of the pre-stressed steel affects the safety of the constructional structure. Once the strength is not high enough, the whole structure will be damaged or even collapsed.

The understanding of the microstructure and its effect on the mechanical properties is necessary for the development of safe and durable steel products as well as to extend the scope of application of the HSLA steels. It is well known that alloying elements' presence provides greater control over microstructure and consequent benefit in mechanical properties [3]. Thus, strength in steels arises from several phenomena including solid solution strengthening, dispersion strengthening and ferrite grain refinement which usually contribute collectively to the observed mechanical properties such as ductility, strength, etc. Y. Tomota *et al.* confirmed that one of the potential ways to increase the work hardening is introduction of the hard second phase which is effective to increase

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not only tensile strength but also uniform elongation in case of fine-grained steel [4]. Similarly, J. E. Kim *et al.* studied the relationships between tensile properties and precipitates of a HSLA steel, concluded that coarsening of originally nano-sized precipitates mainly affects the tensile behavior [5]. As Cr has a tendency to form hard and stable carbides, then strengthens the steel, most of the alloy steels are alloyed with this element. The Cr alloying gives steel the ability to resist softening during tempering and makes the tempered Cr steels hard and wear resistant [6,7]. For a given hardness level, Cr steels need higher tempering temperatures or longer tempering times, than the plain C steels. The presence of Cr carbide also gives structural steels the ability to resist softening at higher temperatures. This effect increases with increasing Cr amount of the steel, but Cr content is usually less than 1.5 wt.% in almost standard HSLA steels. Besides, micro-alloyed steels that contain small additions of alloying elements such as Nb, V, or Ti have been developed for many years and are widely used in modern industry. However, due to the high price of Nb and V, the development of Ti micro-alloyed steels seems to be attracted and getting more attention. Titanium is known as a strong deoxidizer but is usually not used for this purpose. Ti is important in HSLA steels because this element acts as TiN precipitation to suppress the recrystallization and grain growth of austenite, thus providing grain refinement to enhance hardenability and increase ductility [8]. Normally, a Ti content of 0.05 wt.% is typical for this application.

A combination of alloying addition and application of heat treatment or/and thermo-mechanical treatment has been applied to improve the mechanical properties of the HSLA steels. For example, M. K. Banerjee *et al.* has studied the effect of thermo-mechanical processing on the microstructure and characteristics of the low alloy steel containing low carbon content; the steel ingot (ϕ60×300 mm) was hot rolled into the plate of 12.5 mm in the temperature range of 1250 to 750 ^oC; then, the deformed steel was cooled in the various conditions; the ultimate tensile strength (UTS)/yield strength (YS) of the steel increased strongly from 966/707 to 1193/1053 MPa because of adding the alloying elements (e.g. Cr, Ni, Cu, Ti, Nb, Mo) and applying the thermo-mechanical treatment [1]. J. Hannula *et al.* who processed a HSLA steel thermos-mechanically with different contents of Mo and Nb, then subjected to direct quenching treatment, confirmed that final direct-quenched microstructures were martensite and YS varied in the range of 766-1119 MPa [9]. In the other research, the effect of two ways of the hot rolling on the mechanical properties of the 0.08C-1.0Mn-0.02Al-0.011Ti-0.0033N has been investigated [10]. Firstly, the continuous billet of 1150 ^oC was hot rolled directly into the steel plate; secondly, the cold billet was reheated to 1150 ^oC and then rolled into the steel plate. In both cases, the water was sprayed on the surface of the steel right after the final rolling, but the finished temperatures of the plate were controlled at 600 ^oC. Subsequently, the steel was cooled down in the air to room temperature. This result showed that the Ti micro-alloyed steel had higher strengths in the case that the hot direct rolling was applied. Clearly, the quick cooling of the hot rolled steel containing Ti element has a smaller grain size which improved the mechanical properties of the steel.

It can be said that HSLA steel used for the construction has been strengthened by the separately Cr or Ti alloying addition as well as by the heat treatment for many years. However, steels that are simultaneously alloyed with the Cr-Ti and increased mechanical properties by the heat treatment have been seldom studied. Therefore, this paper presents the obtained results on the improvement of strength and microstructure of a HSLA steel grade via alloying with Cr-Ti and heat treatment towards the prestressing application.

2. Experiment

In this research, the experimental procedure was carried out as illustrated in Fig. 1. The main steps included steelmaking, the deformation, and heat treatment in accordance with the practice.

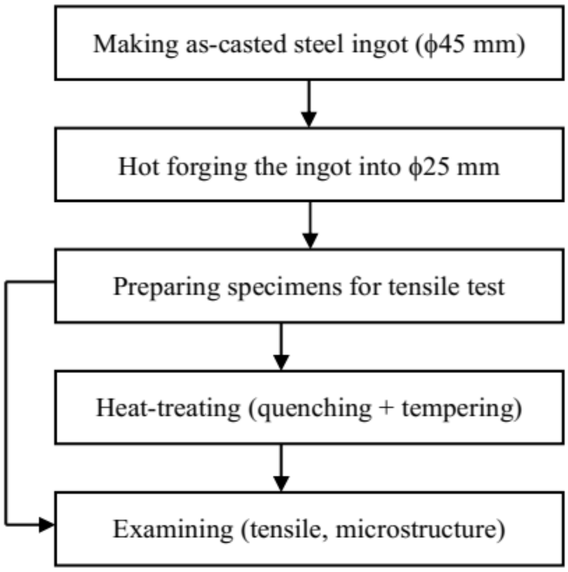


Fig. 1. The experimental procedure.

According to the ASTM A633 (grade C), the chemical compositions of the aimed HSLA steel are listed in Table 1. Based on the theory of the steel hardening and the effect of the alloying elements on the Si-Mn steel, another steel which contained Cr in the range of 1.0-1.5 wt.% and Ti in the range of 0.05-0.10 wt.% have been also prepared.

Table 1. Compositions of the aimed steel (wt.%).

C	Si	Mn	S	P
< 0.20	0.15-0.50	1.15-1.50	< 0.040	< 0.040

Both the steels were melted in the induction furnace, in which the input materials including 5 kg scrap and some ferrous alloys (FeMn80, FeSi45, FeCr65 and FeTi30) were charged with the calculated ratios. All charged materials were cleaned from the dust, oil, the painting and other impurities. The main compositions of the input materials are given in Table 2. Some fluxes such as lime (CaO) and fluorspar (CaF_2) were used to improve the inclusions removal.

The steelmaking step was done in the induction furnace (CHOY 100), as outlined procedure in Fig. 2. An amount of CaO was added into the furnace for the slag forming, as a result, enhancing the desulphurization and dephosphorization. Meanwhile, the CaF_2 helped increasing the fluidity of the surfacial slag which could dissolve the non-metallic inclusions quickly when they floated up to the meniscus.

Table 2. Compositions of the input materials.

Input materials	Compositions (wt.%)				
	C	Mn	Si	Cr	Ti
Scrap	0.20	0.37	0.12	-	-
FeMn80	0,40	80	-	-	-
FeSi45	0,20	-	45	-	-
FeCr65	0,70	-	-	65	-
FeTi30	0,30	-	-	-	30

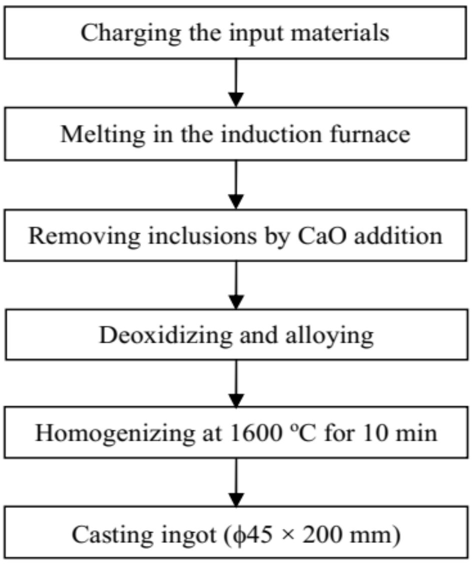


Fig. 2. The steelmaking procedure in the induction furnace.

Fig. 3. Images of the as-casted ingots and forged steel bars in this study.

After completely melted, the liquid steel was kept at 1600 ^oC for 10 minutes for homogenization and then tapped into the metallic mold. The chemical compositions of the two steel grades were analyzed using optical emission spectroscopy (Metal LAB 75/80J MVU-GNR). The steel ingot (45 mm in average diameter) was heated to 1150 ^oC and forged into the average diameter of 25 mm. The finished temperature of the forging process was about 900 ^oC, meaning that the steel stayed in the austenitic region. The as-casted ingots and forged bars are shown in Fig. 3.

After slowly cooling down to room temperature, the steel bar was cut to prepare the specimens for the tensile test. Dimensions of the specimen were according to the standard TCVN 197 (ISO 6892), as seen in Fig. 4. The tensile test was carried out on the Mastet – Holl machine using the strain rate of 10^{-2} mm/s.

Complex chromium-iron carbides go into solution in austenite slowly and hence sufficient heating time is required to be provided before quenching of these steels. Thus, the heat treatment of the steels was performed as the procedure in Fig. 5, where the specimens were heated up to 900 ^oC, hold for 30 minutes, quenched in the water; subsequently tempered at 200 ^oC. The purpose of the tempering step was to decrease (or remove) the interior stress, changing the quenched microstructure of martensite and retaining austenite to other one having more impact toughness. For the prestressed steel, the low tempering treatment was selected for obtaining the tempered martensitic microstructure, removing the stress in the steel, remaining high strength, and improving the ductility of the steel.

At the same time, some samples of both deformed and heat-treated steels were prepared to observe the microstructure and non-metallic inclusion distribution by employing optical microscopy (Axiovert 25) and scanning electron microscopy (Hitachi S-4800).

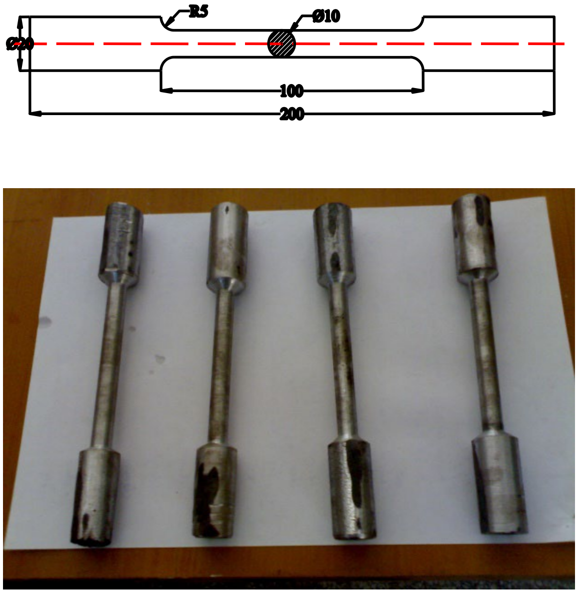


Fig. 4. Dimensions and image of the specimen for tensile test.

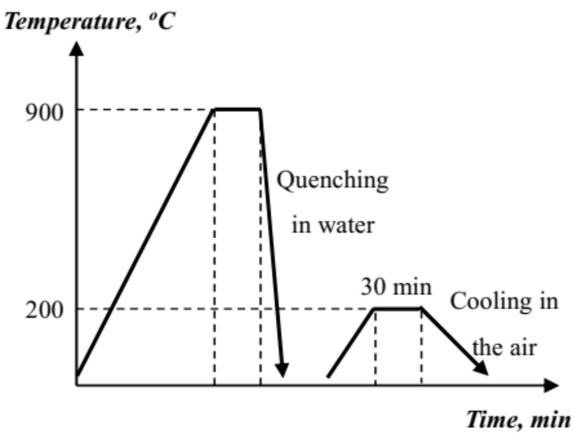


Fig. 5. Heat treated procedure of the specimens.

3. Results and Discussions

Analyzed compositions of the steels were presented in Table 3. It can be seen that the compositions of these steels stayed at the predetermined values. The content of C, Si and Mn were almost the same in steel No. 1 and steel No. 2. The difference between these steels was in the content of Cr and Ti. It can be seen that both the steels contained very low content of S and P which are known as deteriorating impurities in the steel. This resulted from the careful preparation of the input materials, as well as the high cleanness of the scrap which was the main in the input materials.

In the steel melting process, the inclusion removal was paid attention to obtain the highest cleanness of the final steel. Normally, large inclusions float up faster than the smaller ones then the floating inclusions are absorbed by the surface slag. Because the floating process may be intensified by the stirring of the induction force, the induction melting would be an advantage for the inclusions floating in this research.

The result of the tensile tests is given in Table 4, in which the yield strength (YS) and ultimate tensile strength (UTS) are very high while the elongation (A) remains at a moderate value. It has been shown that the heat-treated samples (steel No. 1 and No. 2) possessed both the high YS and the UTS while the deformed samples did not. For instance, the YS and UTS of the deformed steel No. 1 are 408 MPa and 702 MPa, respectively but those of the heat-treated steel No. 1 are 1092 MPa and 1217 MPa, respectively. According to the standard TCVN 6284-5:1997, the UTS of the pre-stressed steel bar must be higher than 1230 MPa. Therefore, the Cr-Ti alloying steel has completely fulfilled the requirement in the case that the heat treatment has been applied. An explanation of this influence will be discussed later.

Table 3. Chemical compositions of the steels.

	C	Si	Mn	Cr	Ti	P	S
No.1	0.19	0.41	1.47	-	-	0.035	0.018
No.2	0.17	0.45	1.49	1.39	0.08	0.026	0.020

Table 4. Result of the tensile test.

	Deformed steel		Heat-treated steel	
	No. 1	No. 2	No. 1	No. 2
YS (MPa)	408	865	1092	1477
UTS (MPa)	702	961	1217	1611
Elongation (%)	20	15	10	10

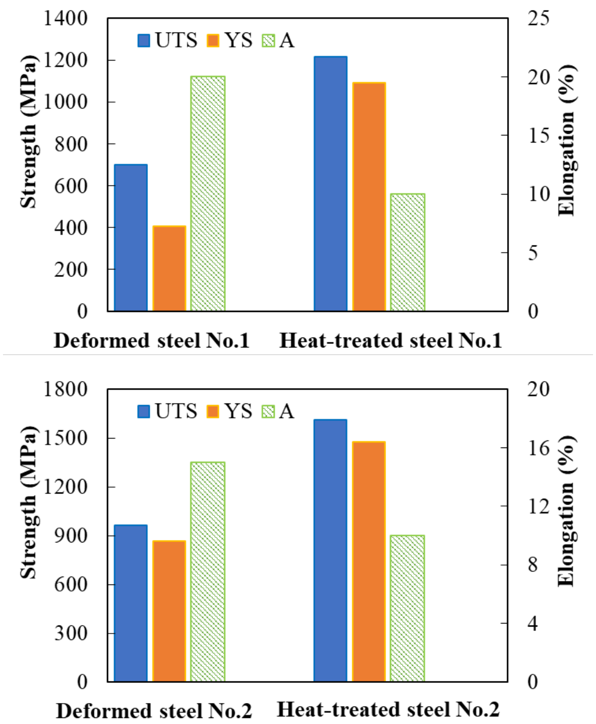


Fig. 6. Comparison of mechanical properties of the deformed and heat-treated steels (No. 1 and No. 2).

Comparison of the mechanical properties of both steels is plotted in Fig. 6. It is revealed that the heat-treated samples containing Cr and Ti obtained a very high YS/UTS ratio (1477/1611 = 0.92), even for the deformed steel (865/961 = 0.90). This can be attributed to hot deformation, phase transformation as well as the presence of alloying elements (Cr, Ti), inhibiting dislocation movement, to effect strengthening with respect to UTS and YS. This result is consistent with conclusions which were found by H. Kobayashi [11] and M. Sasaki [12] who confirmed that Cr was not a strong hardenability agent as compared to some other elements such as Mn or Mo but a strong carbide stabilizer which dissolves into a matrix phase (ferrite or austenite), so the steel thus has been strengthened. Practically, basic metallurgical principles including composition, processing (melting, refining, the deformation, and heat treatment) and microstructure are used to control for production of steel with the desired properties. This means that the steel composition and processing route must be tightly controlled to create the desired microstructure. Mechanical properties of steels are strongly connected to the heat-treated microstructure that generally brings a good hardness and/or tensile strength with sufficient ductility. In the steelmaking industry, the hot rolled steel that stays in the austenitic region can be directly quenched by the water spraying to obtain the martensitic phase and fine grains, resulted in adequate mechanical properties.

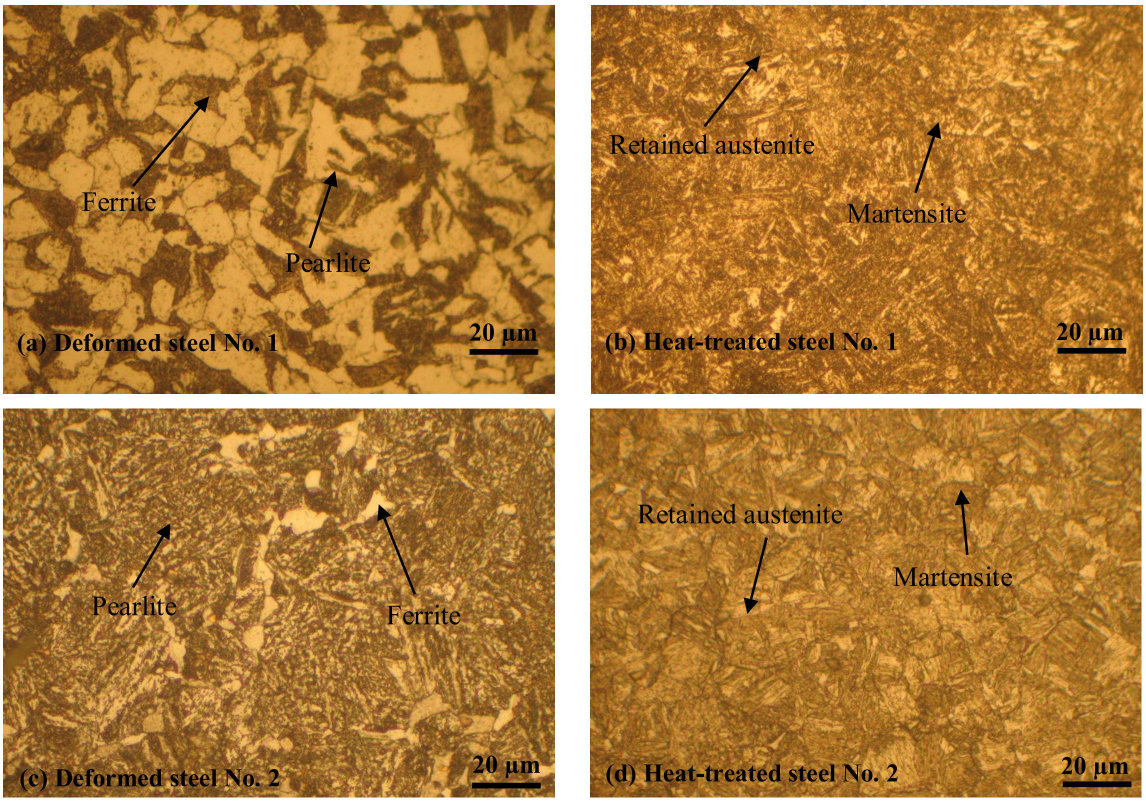


Fig. 7. Microstructures of the deformed and heat-treated steels (No. 1 and No. 2).

Optical micrographs of the present steel observed on cross-section of the samples are indicated in Fig. 7. The microstructures are very homogenous with a soft (ferrite or retained austenite) and strengthening (pearlite or martensite) phases. In Fig. 7a and 7c, the observed microstructure of the deformed steel No. 1 included approximately 70% ferrite (white color) and 30% pearlite (black color), a bit higher ratio of the pearlite to ferrite phase was seen in the deformed steel No. 2 with Cr-Ti alloying. In comparison with steel No. 1, a smaller grain size was also found in steel No. 2. This result was in the agreement with the UTS that appeared in Table 4, as other studies confirmed that the steel with smaller grains gained higher tensile strength [12]. Fig. 7b shows the microstructure of the heat-treated steel No. 1 consisting of the retained austenite (white color) and the martensite (black color), but it is hard to see the retained austenite in the Cr-Ti alloying steel No. 2 (Fig. 7d). The obtained fine grain microstructure of the steel No. 2 must have enhanced the mechanical properties of the steels obviously. This result was similar findings to the study in which Mo and Nb additions led to a refined martensitic microstructure that resulted in a good combination of strength and toughness [3,9]. In addition, multi-microalloying can lead to the formation of carbide and nitride particles which can further influence the mechanical properties of the steels. As a result, the strength of the Cr-Ti alloying steel No. 2 has been improved.

To ascertain the microstructural observation, JmatPro® software (version 7) was used to calculate the phases of the deformed and heat-treated steel samples. The calculated results are shown in Fig. 8, where the calculated results are quite matching with the optical micrographs. The phase ratio of pearlite/ferrite increases from 26/74 in the deformed steel to 40/60 in the heat-treated steel. Meanwhile, martensite is the prominent phase in both heat-treated steels. However, a small amount of the retained austenite is usually found in the quenched steel. It is not exceptional for this experiment. The retained austenite was present in both the heat-treated steels.

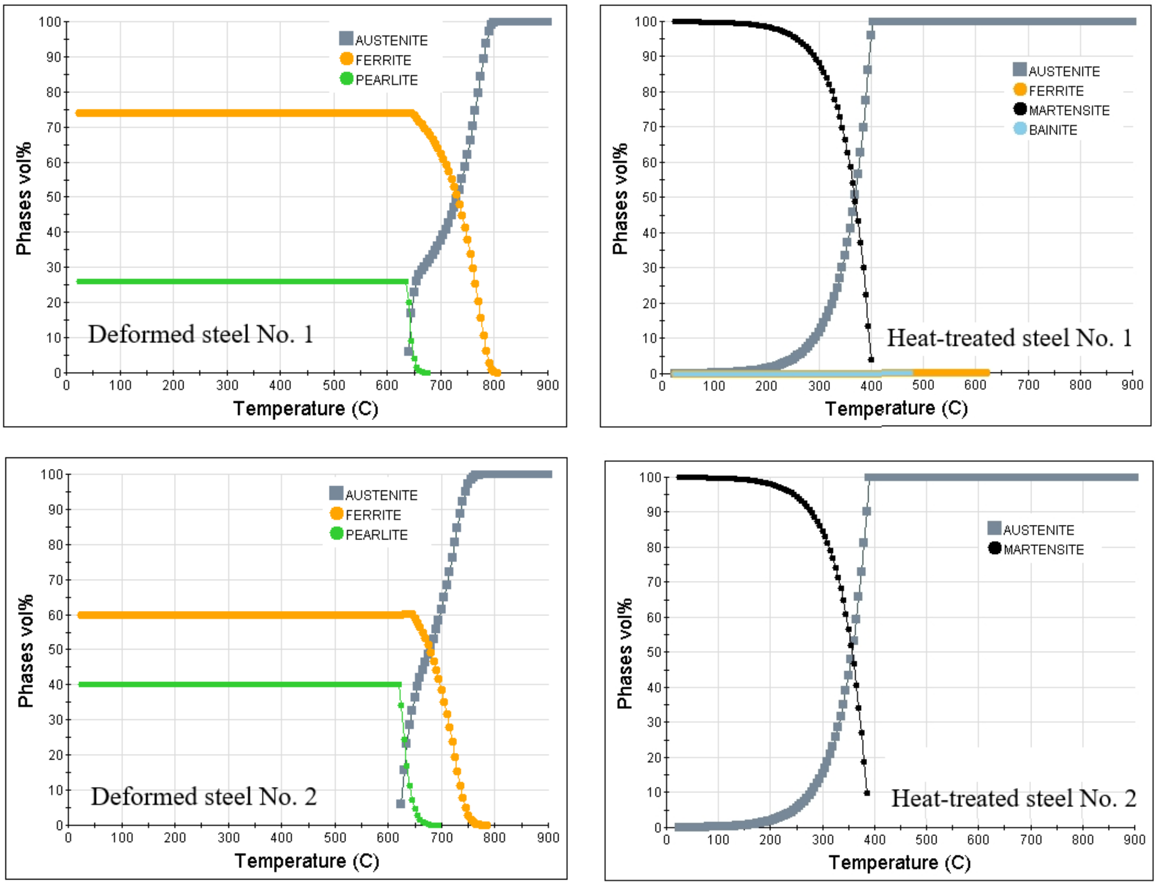


Fig. 8. Phase fractions of the deformed and heat-treated steels (No. 1 and No.2) calculated by JmatPro® software.

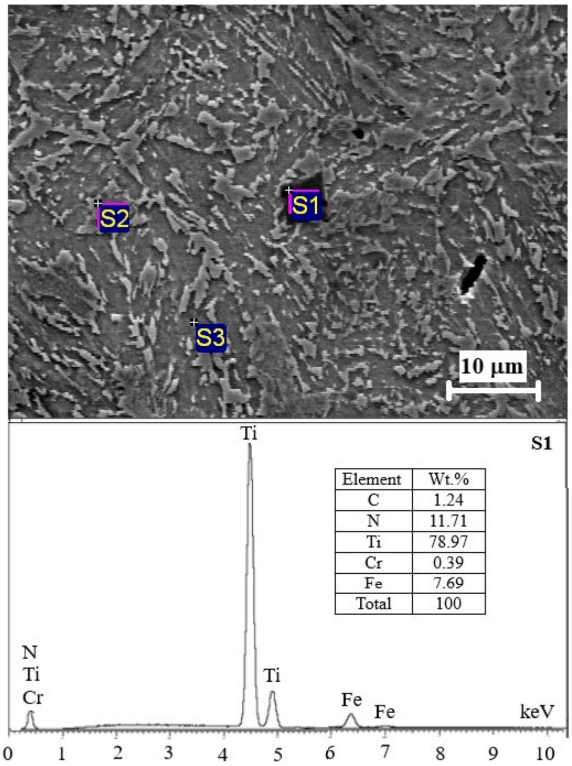
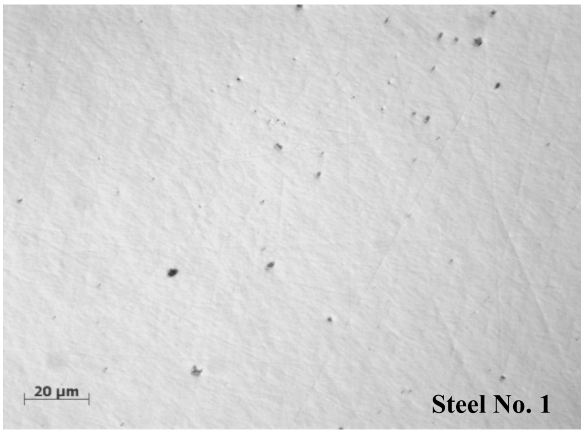


Fig. 9. SEM- EDS result of the Ti-precipitate in heat-treated steel No. 2.

Differing from Cr which strengthens solid solution, Ti micro-alloyed steels are strengthened by the mechanism that involves a combination of the grain refinement and the precipitation which depends on the amount of alloy additions and processing method. M. Sasaki confirmed that Ti in low alloy steels formed some compounds that provided grain refinement precipitation strengthening due to formation of TiN precipitates which retarded grain boundary movement in austenite [12]. However, it is suggested that Ti can be used only in fully killed steels, namely Al-killed steels, because Ti is able to form other compounds than Ti oxide. Some precipitates can have a beneficial effect on steels properties by nucleating acicular ferrite during the austenite to ferrite phase transformation, especially in low carbon steels. Ti also forms its nitride at very high temperatures and is therefore used to reduce grain growth of austenite during hot rolling of plates. As mentioned above, Ti is important in low alloy steels because of the formation of TiN precipitates. To ascertain the TiN existence in the Cr-Ti alloying steel, SEM (scanning electron microscopy) and EDS (energy dispersive X-ray spectrometer) analysis were employed. Fig. 9 shows the EDS analysis of the fine precipitates in microstructure of the Cr-Ti alloying steel. It indicates the presence of the TiN precipitate which was effective grain refiner in the reheated or the continuous casting steels. In some steel grades, Ti is used for the precipitation of the Ti(C,N) which is stable at high temperatures, resulting in the reduction of the grain growth and increase of the toughness [6].

It is known that non-metallic inclusions are naturally occurring and typically undesired products that are formed into various types depending on their favorable thermodynamic conditions during steel production. They are constituted by glass-ceramic phases embedded in steel metal matrix. The type and appearance of these non-metallic inclusions depend on factors such as grade of steel, steel making process, and secondary metallurgy. Despite the presence of non-metallic inclusions in steels with a small percentage (0.01-0.02 wt.%), they have a significant effect on the properties of steels, causing dangerous and serious defects such as brittleness and a wide variety of crack formations [13]. Generally, the non-metallic inclusions affect the properties of steels such as the tensile strength, deformability, toughness, fatigue, corrosion resistance, etc. In steelmaking, many elements such as Si, Mn and Al are acceptable as part of the steel composition have a high affinity for oxygen and can thus be used as deoxidizers, forming non-metallic deoxidation products when added to the liquid steel. In the case of sulfur, on the other hand, only elements with low solubility in iron (such as Ca and Mg) or rare-earth metals have sufficiently high affinity to sulfur to form non-metallic sulfides at the liquid steel temperatures. Thus, most of the sulfur in steel must be removed from the liquid steel by slag refining and the rest, by precipitation reactions occurring mostly during solidification. Since control of non-metallic inclusions plays an important part in the improvement of steel strength, the non-metallic inclusions distribution in the steels was observed by optical microscopy, as shown in Fig. 10. A few of the small non-metallic inclusions were found in the investigated steels. Clusters of the inclusions or accumulations of the small inclusions were not observed in the steels. This result also supported the high strengths and the good elongation of the steels, as given in Table 4.

There are many types of non-metallic inclusions which are present in the steel despite that the deoxidation has been done. The reason is the reoxidation of liquid steel during the casting process in which the melt contacts with the oxygen in the atmosphere, with the entrapped slag or the refractory [13]. Among inclusions that formed during reoxidation, alumina is the most unexpected because it is non-deformable and irregularly distributed. Therefore, the reoxidation of liquid steel needs to be minimized in the production of pre-stressed steel; otherwise, the mechanical properties of the steel are decreased due to increase of the inclusions. In accordance with the current steelmaking technology, control of inclusions must be applied using advanced refining technology such as vacuum, argon purging, synthetic slag, etc.



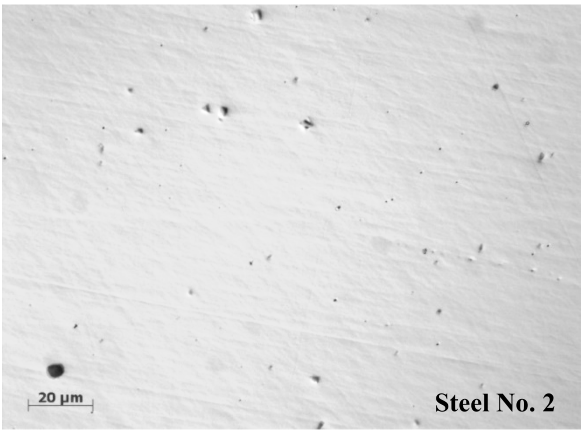


Fig. 10. Distribution of non-metallic inclusion in the deformed steels.

4. Conclusion

Production of the steel with high tensile strength and ductility can be done by a combination of Cr-Ti alloying and heat treatment. A laboratory scale experiment has been done to improve the strength of a HSLA steel for the prestressing application. The steel was melted in the induction furnace with the aim of controlling the precise compositions of grade C (according to ASTM A633) and minimizing the inclusions. It has been concluded that the application of hot deformation, quenching and tempering improved the tensile strength of the original steel grade as well as the Cr-Ti alloying grade. After deformation and heat treatment, the UTS/YS of the original steels was 702/408 MPa and 961/865 MPa, respectively. A proper microstructure with the hardened martensitic phase, fine Ti-precipitated compounds and fewer inclusions contributed to the improvement of the strength of the Cr-Ti alloyed steel, of which UTS/YS was 1611/1477 MPa and the elongation was 10% for the heat-treated condition. These mechanical properties fulfilled the requirement of the prestressing concrete and other application.

References

[1] M. K. Banerjee, P. S. Banerjee, S. Datta, Effect of thermo-mechanical processing on the microstructure and properties of a low carbon copper bearing steel, ISIJ Int., vol. 41, no. 3, pp. 257-261, 2001. https://doi.org/10.2355/isijinternational.41.257

[2] S. Ma, H. M. Li, B. J. Tang, Research on impact performance of prestressed steel strand, IOP Conference Serries Earth and Environmental Science, vol. 634, no. 1, Article ID 012124, 2021. https://doi.org/10.1088/1755-1315/634/1/012124

[3] Z. Q. Li, L. H. Qian, S. A. Liu, L. Zhan, S. J. Qin, Preparation and mechanical behavior of ultra-high strength low-carbon steel, Materials, vol. 13, pp. 459-472, 2020. https://doi.org/10.3390/ma13020459

[4] Y. Tomota, A. Narui and N. Tsuchida, Tensile behavior of fine-grained steels, ISIJ Int., vol. 48, no. 8, pp. 1107-1113, 2008. https://doi.org/10.2355/isijinternational.48.1107

[5] J. E. Kim, J. B. Seol, W. M. Choi, C. G. Park, Isothermal treatment effects on precipitates and tensile properties of an HSLA steel, Met. Mater. Int., vol. 24, pp. 525-531, 2018. https://doi.org/10.1007/s12540-018-0041-7

[6] A. W. El-Morsy, A. I. Z. Farahat, Effect of Cr and thermomechanical processing on the microstructure and mechanical properties of advanced high-strength steel, J. Eng. Mater. Technol., vol. 140, no. 2, pp. 2, Article ID 021005, 2018. https://doi.org/10.1115/1.4038393

[7] B. M. Kim, S. J. Kim, and H. S. Kim, Effect of alloying element (Cr, Mn) on corrosion properties of the high strength steel in 3.5% NaCl solution, Advan. Mater. Sci. Eng., Article ID 7638274, 2018. https://doi.org/10.1155/2018/7638274

[8] X. D. Huo, J. N. Xia, L. J. Li, Z. W. Peng, S. J. Chen and C. T. Peng, A review of research and development on titannium microalloyed high strength steels, Mater. Res. Express., vol. 5, no. 6, Article ID 062002, 2018. https://doi.org/10.1088/2053-1591/aacb61

[9] J. Hannula, D. Porter, A. Kaijalainen, M. Somani, J. Komi, Mechanical properties of direct-quenched ultra-high-strength steel alloyed with molybdennum and niobium, Metal, vol. 9, no. 3, pp. 350-363, 2019. https://doi.org/10.3390/met9030350

[10] K. Kunishige, N. Nagao, Strengthening and toughening of hot-direct-roll steel by addition of a small amount of titanium, ISIJ Int., vol. 29, no. 11, pp. 940-946, 1989. https://doi.org/10.2355/isijinternational.29.940

[11] H. Kobayashi, Microstructure development in Ti bearing interstitial free steel with simulated hot rolling practice, ISIJ Int., vol. 32, no. 7, pp. 873-881, 1992. https://doi.org/10.2355/isijinternational.32.873

[12] M. Sasaki, Refinement of austenite grain in carbon steel by addition of Titanium and boron, ISIJ Int., vol. 48, no. 3, pp. 340-343, 2008. https://doi.org/10.2355/isijinternational.48.340

[13] A. L. V. Costa e Silva, Non-metallic inclusions in steels - origin and control, J. Mater. Res. Technol., vol. 7, no. 3, pp. 283-299, 2018. https://doi.org/10.1016/j.jmrt.2018.04.00