Effect of nickel additions on microstructure evolution and mechanical properties of low-alloy Cr-Mo cast steel

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Abstract. This paper presents investigation of nickel additions on the low-alloy Cr-Mo cast steel which was normalized at temperature of 920 °C. In this experiment, approximately 0.3, 0.5, and 1.0 wt% Ni was added into the Fe-1.0Mn-0.8Cr-0.4Mo cast steel. The microstructure of low-alloy Cr-Mo cast steel was observed by optical microscope and scanning electron microscope, and the phase compositions were identified by EDX analysis. Tensile, hardness, and Charpy impact tests were conducted to investigate correlation between nickel additions to microstructure characteristics and mechanical properties. The results show that increasing nickel from 0.3 to 1.0 wt% on the alloys has improved the strength without sacrificing the impact toughness. Ni addition into low alloy steel increased the austenite stability due to the grain refinement. The strength was found increase linearly with Ni addition which may caused mainly by solid solution strengthening due to Ni dissolved into the ferrite matrix.

1. Introduction
Low-alloy Cr-Mo steels are used in various application such as the components of power station boilers with application in extreme temperature up to about 560°C [1]. These steels also widely used in application as advanced high strength steel (AHSS) which have microstructure of carbide free bainitic steel in rail and protective armor steel [2,3]. Alloying is one of techniques to increase the materials properties such as ductility, strength, toughness, corrosion and oxidation resistance. Small amount of Cr, Mo, Ni and C were added into steel to make better strength, toughness, and corrosion resistance [4]. One method of the steel strengthening mechanism which is known as the solid solution is performed by alloying of small amounts of dissolved atoms [5]. The mechanical performance of metals which resulted solute atoms dissolved in solvent depending on the amount and type of the solutes [4].

Addition of Mn and Ni increased the hardness which was attributed mainly to solid solution strengthening due to part to formation of hard phases [6]. Mn and Ni have similar effect on phase transformation and grain size, both were also responsible for hardening but effect of Mn is more noticeable [6,7]. Ni is known as an element which contribute to improve the hardenability and heat resistance of steel [8]. K. Kim et al. suggested increasing Ni content on Q & P treated steel improved
the tensile strength, elongation and hardness due to solid solution mechanism and the grain refinement effect [9].

Mn and Ni influence impact toughness in different ways. B.Y. Kang et al. suggested for low Mn content (0.5%), ductile-to-brittle transition temperature was not any increase even with the higher hardness by Ni addition. But, in the case of Ni was co-present with a high Mn content (1.6%), with a large addition of Ni the microstructure became predominantly martensite which susceptible to intergranular brittle crack propagation [6]. When Mn and Ni increased then the proportion of acicular ferrite was increased, bainite and M-A constituent began to arise. Furthermore, the higher Mn and Ni tend to promote micro segregation of Mn, Ni, and Si elements in a network or parallel to grain boundaries [7].

Compared to the other carbide-forming elements (Cr, Mo, W), Ni tends dissolved into the ferrite matrix instead of forming carbides. By addition of Ni into the material, carbide-forming elements were suppressed to be the solid solution in the matrix [8]. The effect of Ni addition on the low alloy steel provides some benefits, Ni does not form secondary phases, it remains in the solid solution strengthening mechanism in the ferrite matrix [10]. Ni distributed in the ferrite matrix uniformly. Ni which dissolved in the ferrite matrix increases the stacking fault energy, so that at low temperature promotes dislocation crossing slip, and thus boosts power consumption of crack propagation, finally increase of the low-temperature impact toughness [11]. The retained austenite is part of M-A constituent in steel, it is mainly found in the lower Ni content that indicated that the transformation process could be more completely by increasing Ni content. The large volume fraction of M-A was mainly found in the lower Ni content effect to reduce the toughness. The more Ni content, the less retained austenite and the more the transformation completed [12].

Ni additions increased austenite grains stability by expands the austenite regions due to the grain refinement and lowered the ferrite transformation temperature so that refined the low alloy steel grains size [9,10,12]. A consequence of the lower ferrite transformation temperature is that Ni promotes the formation of acicular ferrite at the expense of other kinds of ferrite such as side plate ferrite and grain boundary ferrite [7,10,12]. Ni improves the impact toughness by the grain size refinement in the columnar zone as well as by Ni by itself [6]. Y. Sun et al. reported increasing 0-1.8% Ni on high ductility ductile iron increased low temperature impact toughness significantly, the highest toughness reached with 0.71% Ni addition, then descents [11].

This paper investigated effect of nickel additions to improve the hardness of low alloy Fe-1.0Mn-0.8Cr-0.4Mo steel without deteriorate impact toughness. This study including observations of microstructure and phase compositions, tensile and hardness measurements, and performance of impact toughness at room temperature.

2. Experimental method

2.1 Melting and casting

The medium carbon steel scraps were melted in a medium frequency induction furnace of 200 kg capacity. Additional alloying which consist of Fe-Mn, Fe-Cr, Fe-Mo, and pure Ni were supplied into the molten metal in induction furnace until low alloy Fe-1.0Mn-0.8Cr-0.4Mo cast steel produced. Pure Ni was added to the melt to produce three different content of nickel (0.3%, 0.5%, and 1.0%). Furthermore, the melt was heated to the temperature of 1700°C.

The small amount of melt was poured as test specimens for spectrometric analysis. The chemical composition was measured by optical emission spectrometer during controlling the levels of nickel content in the low-alloy Cr-Mo cast steel. When the specified nickel content achieved, the melt was poured at temperature range of 1620-1650°C for 6 to 7 seconds into Y-block sand molds which made from sand cast and alpha resin binder, and finally the melt was allowed cooling to room temperature. After completely solidification, the Y-block samples were heat treated of normalizing by electric furnace
to temperature of 920°C for 10 minutes and allowed cooling to room temperature in the atmosphere. The chemical analysis result of the casting is presented in Table 1.

![Figure 1](image1.png)

(a) Pouring into Y-block sand molds and (b) Y-block sample

![Figure 2](image2.png)

Figure 2. Heat treatment schematic

### Table 1. Chemical analysis of the low-alloy Cr-Mo cast steel samples (%wt.)

| Sample No. | C   | Si  | Mn  | P   | S   | Cr  | Mo  | Ni  | Fe   |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|------|
| 1          | 0.40| 0.20| 1.00| 0.01| 0.01| 0.80| 0.40| 0.30| Bal.  |
| 2          | 0.40| 0.20| 1.00| 0.01| 0.01| 0.80| 0.40| 0.50| Bal.  |
| 3          | 0.40| 0.20| 1.00| 0.01| 0.01| 0.80| 0.40| 1.00| Bal.  |
2.2. Microstructure
The test specimens for metallography examination were prepared in the standard procedure, roughed by abrasive paper, polish using diamond paste, and etched with 3% Nital (3 ml HNO$_3$ + 97 ml ethanol). Microstructure of the as cast low-alloy Cr-Mo samples were observed using an optical microscope and continued with a scanning electron microscope (SEM) which equipped with an EDX analyzer.

2.3. Mechanical tests
The mechanical tests i.e. tensile, hardness, and impact toughness were performed on each test specimens of 0.3%, 0.5%, and 1% Ni addition. The tensile tests were conducted at room temperature using a tensile testing machine with reference of JIS Z 2241 standard specification. To evaluate the impact toughness, the Charpy V-notch samples of size 10 mm x 10 mm x 55 mm were prepared and tested using impact testing machine at room temperature according to JIS Z 2242 standard specification. Hardness measurements were carried out at room temperature using Rockwell C hardness tester with reference of JIS Z 2245 standard specification.

3. Results and discussion
3.1 Microstructure investigation
The typical microstructures of Ni additions into the low alloy Fe-1.0Mn-0.8Cr-0.4Mo steel after normalizing at 920°C for 10 minutes were observed by optical microscope and back scatter electron-scanning electron microscope (BSE-SEM). The typical microstructures of Ni-added low alloy Cr-Mo cast steel are shown in Figure 3 (observation by optical microscope) and Figure 4 (observation by scanning electron microscope). It seems that the microstructure contains carbide-free bainitic ferrite phase. Some elements such as manganese, silicon, chromium and molybdenum are important elements in carbide-free bainitic steel of high strength low alloy steels [2,3]. Base on optical microscope images in Figure 3, it was observed that increasing Ni affect to enlarge light areas. The BSE-SEM results as shown in Figure 4 also indicated that increasing Ni affect to increase light bainitic ferrite phase.

Analysis by image analyzer was conducted to measure light and dark area percentage. The result show that the light areas increased when nickel content increased. The light areas percentage of each Ni content were 47.5% (0.3% Ni), 60.8% (0.5% Ni), and 73.5% (1% Ni). It seems that increasing Ni affect to increasing light bainitic ferrite region.

Analysis of Fe, C, Ni, Cr, Mo, and Mn elements distribution was performed by using color mapping by x-ray diffraction-scanning electron microscope (EDX-SEM) for the sample of 1% Ni addition. Color mapping analysis in Figure 5 shows Ni and other elements (Fe, C, Cr, Mo, and Mn) did not segregated in the certain area, but they are uniformly distributed on both light and dark areas. It could be these elements dissolved in the bainitic ferrite phases, and substitute Fe in the crystal lattice with atom substitutional solid solution mechanism. More Ni added makes more Fe substituted by Ni in crystal structure. Similar result was reported by Y. Sun et al. in their study with ductile iron containing 0-1.8 wt% Ni. According to them Ni element distributed uniformly in the ferrite matrix, furthermore the tensile strength and the low temperature impact toughness increased with Ni addition up to 0.71 wt% [11].
Although Cr, Mn, and Mo elements are carbide-forming elements, they are also dissolved in the ferrite matrix with substitutional mechanism. It could be presence of Ni suppressed these carbide-forming elements to be solid solution in the ferrite matrix and avoid carbide segregation. In an earlier study reported by Y. Zhang et al., Ni tends dissolved into the matrix instead of forming carbides compared to the other carbide-forming elements such as Cr, Mo, W). By addition of Ni into the material, carbide-forming elements were suppressed to be the solid solution in the ferrite matrix [8].
Further analysis by energy dispersive X-ray spectroscopy (EDX) was carried out to identify certain elements which was visually observed in the BSE image. The observation result show that the dark areas containing Cr and Mn, while light areas only containing Ni without Cr and Mn. Since the atomic weight of Ni higher than Cr and Mn, the phase that containing Ni shown lighter image. It seems that Ni dissolved only in light areas. Figure 6 shows Ni-dissolved bainitic ferrite (light phase) and Ni-free bainitic ferrite (dark phase). It seems that presence of Ni formed Ni-dissolved bainitic ferrite and suppressed Cr and Mn elements to be dissolved into the Ni-free bainitic ferrite.

**Figure 6.** Ni-dissolved bainitic ferrite phase and Ni-free bainitic ferrite phase in 1.0% Ni added Cr-Mo steel.
3.2 Mechanical properties

Mechanical test results of the samples with various Ni content are presented in Table 2. The mechanical test results indicated that the higher Ni content increased the yield strength, tensile strength and hardness, while the impact toughness relatively unaffected. Figure 7 shows effect of Ni additions on the tensile strength, hardness, and impact energy of the samples material. Tensile strength increased significantly by increasing of Ni, which shows 1040 N/mm² (0.3% Ni), 1200 N/mm² (0.5% Ni), and 1350 N/mm² (1% Ni). The hardness also tends to increased linearly by increasing Ni. The hardness improved from 30 HRC at 0.3% Ni to 44 HRC at 1% Ni. Ni additions in low-alloy Cr-Mo cast steel from 0.3% to 1% have improved strength and hardness without sacrificing impact toughness.

Table 2. Yield strength, tensile strength and impact energy of the low-alloy Cr-Mo cast steel samples

| Sample No. | Yield Strength (MPa) | Tensile Strength (MPa) | Total Elongation (%) | Hardness (HRC) | 25 °C Impact Energy (J) |
|------------|----------------------|------------------------|----------------------|----------------|------------------------|
| 1          | 791                  | 1037                   | 9                    | 30             | 11                     |
| 2          | 1052                 | 1202                   | 2                    | 40             | 10                     |
| 3          | 1177                 | 1351                   | 1.7                  | 44             | 9                      |

Figure 7. Mechanical test results of samples with 0.3%, 0.5%, and 1% Ni: (a) tensile strength, (b) hardness, (c) impact energy

To verify the hardness of Ni-dissolved bainitic ferrite phase and Ni-free bainitic ferrite phase, microhardness Vickers test were performed on samples. The result shown that the average hardness of Ni-dissolved bainitic ferrite phases were 610 VHN (56 HRC) compared to only 350 VHN (36 HRC) on Ni-free bainitic ferrite phases. This is indicated that the solid solution strengthening with Ni resulting higher strength compared to Cr and Mn. Stress field within lattice caused by substitutional of larger atoms than Fe (Ni) resulting the compressive strains, whereas caused by substitution of smaller atoms (Cr, Mn) resulting the tensile strains. Stress field increases the lattice strain by dislocation, resulting strengthening of nickel dissolved bainitic ferrite phase. The strength was improved due to the interaction of local stress fields and dislocation that impede dislocation movement. B.Y Kang et al. suggested that addition of Ni increased the hardness which was attributed mainly to solid solution strengthening due to part to formation of hard phases [6].

When conducted the impact test, compressive strain within the lattice resulting by substitution Ni in crystal lattice would absorb the impact energy, causing the toughness of Cr-Mo steel was not significantly change. Other reason, strength and hardness increased without sacrifice impact toughness due to presence of Ni that promoted the grain size refinement. Finer grain size causing more grain boundaries present. Furthermore, more energy required for the crack propagation path so that improves the strength and toughness.
Figure 8. Tensile strain field within lattice caused by substitutional of Ni and Cr/Mn

4. Conclusions
Effect of Ni additions into low-alloy Cr-Mo cast steel has been investigated. The results show that increasing Ni from 0.3% to 1% has improved the tensile strength and hardness while the impact toughness did not change significantly. Ni addition contributed to improve the strength by solid solution strengthening mechanism. Fe substituted by Ni in ferrite matrix by substitution solid solution mechanism resulting compressive strain field within crystal lattice, and causing strengthening of nickel dissolved bainitic ferrite phase. Compressive stress would absorb the impact energy resulting the improvement of toughness resistance. Ni additions into low-alloy Cr-Mo cast steel promotes finer grains size and more grain boundaries present. Consequently, there will be more energy required for the crack propagation path, it improves the strength and toughness.

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