

CHAPTER I

INTRODUCTION

1.1 Rationale of the study

In the steelmaking industry, hot rolling mill rolls are essential forming tools used to shape semi-finished flat and long products (Tommy & Collins, 2002). Similar to other forming tools, work rolls are subjected to direct contact with hot steel plates, leading to progressive surface degradation during operation. Once this deterioration reaches a critical level, the rolls must be replaced either to maintain product quality or to prevent catastrophic failure. Owing to their vital role in steel production, work rolls in the finishing stands of hot-strip mills are generally produced as composite components, consisting of a wear-resistant outer shell and a tough, ductile core (Matsubara et al., 1996; Tommy & Collins, 2002).

The development of materials for hot work rolls has progressed from low-alloyed chilled cast iron to more advanced alloys such as adamite (e.g., hyper-eutectoid Ni-Cr steels), Ni-hard irons, and high-Cr cast iron (Matsubara et al., 1996; Tommy & Collins, 2002). Among these, high-Cr cast iron has been widely adopted due to its excellent wear and thermal resistance (Laird et al., 2000; Matsubara et al., 1996). However, its microstructure, characterized by a high fraction of eutectic carbides, can significantly reduce toughness, thereby limiting roll durability (Hashimoto et al., 1992; Laird et al., 2000; Morikawa et al., 2014). With the increasing demands for higher productivity and product quality in modern steel mills, the design of advanced roll materials with superior performance has become a critical research focus (Morikawa et al., 2014; Hashimoto et al., 1992; Sano et al., 1992; Hashimoto et al., 1995; Takigawa et al., 1997; Opapaiboon et al., 2025a; Goto et al., 1992; Kudo et al., 1992).

Multi-alloyed white cast iron has emerged as a promising candidate for such applications, owing to its high resistance to abrasive wear (Matsubara et al., 1996). This alloy incorporates multiple carbide-forming elements, including chromium (Cr), molybdenum (Mo), tungsten (W), and vanadium (V). These elements combine with carbon (C) to form hard carbides such as MC, M_2C , M_6C and M_7C_3 which impart exceptional wear resistance due to their high hardness. Moreover, residual alloying

elements dissolved in the matrix strengthen the alloy through the precipitation of secondary carbides and martensitic transformation during heat treatment. A typical alloy composition includes approximately 5 wt% each of Cr, Mo, W, and V, together with 2 wt% C (Matsubara et al., 1996). (hereafter the wt% is expressed by %). More recently, cobalt (Co) has been introduced to enhance thermal stability and mechanical strength at elevated temperatures.

From the perspective of toughness, hypoeutectic compositions of multi-alloyed white cast iron are generally preferred. Their solidification begins with the crystallization of primary austenite (γ_p), followed by multiple eutectic reactions involving austenite and carbide (Boccalini, 2011; Matsubara et al., 1994; Sasaguri et al., 2005). The type, morphology, size, and volume fraction of carbides can be tailored through compositional adjustments and cooling rate (Boccalini, 2011; Matsubara et al., 1994; Sasaguri et al., 2005; Wu et al., 1996; Wu et al., 1995; Wu et al., 1997). Furthermore, heat treatment is crucial in optimizing mechanical properties. Similar to high-Cr cast irons and tool steels, heat treatment of multi-alloyed white cast iron involves destabilizing retained austenite at high temperature, where secondary carbides precipitate and promote the transformation of unstable austenite into bainite or martensite. Subsequent tempering relieves residual stresses and further reduces the retained austenite fraction formed during hardening.

Previous studies by our group have investigated the solidification behavior (Hashimoto et al., 2004b; Matsubara et al., 1994; Opapaiboon et al., 2022; Sasaguri et al., 2005; Wu et al., 1996; Wu et al., 1995; Wu et al., 1997), heat treatment response (Hashimoto et al., 2004a; Inthidech & Matsubara, 2020; Inthidech et al., 2021b; Matsubara et al., 1999; Meebupha et al., 2017; Opapaiboon et al., 2019a; Opapaiboon et al., 2022; Opapaiboon et al., 2024; Opapaiboon et al., 2015), and abrasive wear resistance (Hashimoto et al., 2006; Hashimoto et al., 2007a; Hashimoto et al., 2007b; Chang et al., 2008; Opapaiboon et al., 2019b; Inthidech et al., 2021a; Opapaiboon et al., 2025b) of multi-alloyed white cast irons with basic alloy compositions. To further improve performance, it is essential to investigate the role of individual or combined alloying elements in influencing phase transformation, heat treatment behavior, wear resistance, and fracture toughness. Earlier work has systematically clarified the effect of C (Opapaiboon et al., 2015), Cr (Opapaiboon et al., 2019a), Mo (Meebupha et al., 2017; Opapaiboon et al., 2022), W (Inthidech et al., 2021b), and V (Opapaiboon et al.,

2024) on the heat treatment response of these alloys, revealing that each element exhibits an optimal concentration that maximizes tempered hardness. Achieving hardness and wear resistance beyond these limits requires the addition of stronger carbide-forming elements capable of producing extremely hard eutectic carbides.

As basic knowledge, wear is alteration of a solid surface by progressive loss or progressive displacement of material due to relative motion between that surface and a contacting substance or substances. In industrial applications, abrasive wear resistance of materials is an important factor for machine parts so as to avoid failure due to load or stress during operation. Even under the normal condition, the parts or components of machines undergo wear by abrasive particles. The abrasive wear can be classified into two groups: two-body and three-body-types (ASTM G40, 2018). Two-body type abrasive wear occurs when the hard particles which produce the wear of one body are fixed on the surface of the opposing body such as jaw crushers and sliding down a chute. In the three-body-type abrasive wear, the wear is produced by loose particles introduced or generated between the contacting surfaces. The abrasive particles move in a free rolling on the worn surface. This type of abrasive wear can be seen in pulverizing of the cement clinkers. Generally, three-body abrasive wear is lower deteriorated when compared with two-body abrasive wear because there is little wear loss from free rolling and sliding of particles (Zum Gahr, 1987).

Niobium (Nb) is a potent carbide former that produces niobium carbide (NbC) with a hardness of 2400-3000 HV (Laird et al., 2000). NbC generally crystallizes as a primary phase during solidification. Several studies (Filipovic et al., 2013; Bedolla-Jacuinde, 2001; Gao et al., 2016; Bedolla-Jacuinde et al., 2019; Kim et al., 2003; He-Xing et al., 1993; Fiset et al., 1993; Penagos et al., 2017; Kesri & Durand-Charre, 1987; Bedolla-Jacuinde et al., 2015; Zhi et al., 2008; Pourasiabi & Gates, 2021; Boccalini et al., 2008) have reported that NbC refines the as-cast microstructure and enhances abrasive wear resistance in white cast irons. However, the formation of primary NbC consumes significant carbon, potentially reducing the carbon content of the remaining liquid and thereby altering the solidification mode from hyper-eutectic to eutectic or even hypo-eutectic (Boccalini et al., 2008). This shift affects the liquidus and eutectic temperature as well as the solidification sequence. Niobium also exhibits a low partition coefficient in austenite (<0.02) (Boccalini et al., 2008; Laird et al., 2000), indicating that most Nb is consumed in the formation of NbC or mixed MC carbides.

Moreover, relatively large primary NbC particles can shield the surrounding matrix, thereby improving wear resistance (Boccalini et al., 2008; Ichino et al., 1997; Kim et al., 2003; Kusumoto et al., 2017).

In centrifugal casting (CF), which is widely used for roll manufacturing, MC carbides with low specific gravity tend to segregate toward the inner surface of the shell under centrifugal force. To counter this, the use of niobium has been shown to promote the formation of (V, Nb)C complex carbides with a specific gravity closer to that of the molten metal, thereby reducing segregation during CF processing (Boccalini et al., 2008; Hashimoto et al., 1995; Morikawa et al., 2014; Sano et al., 1992; Takigawa et al., 1997).

Given these attributes, niobium is considered a promising alloying element for multi-alloyed white cast irons. Nevertheless, its influence on heat treatment behavior and abrasive wear resistance has not been systematically addressed. Therefore, the present study investigates the effect of Nb additions on the heat-treatment response and abrasive wear resistance of multi-alloyed white cast iron.

1.2 Aims of thesis

The objective of this thesis is to clarify the effect of niobium content on heat treatment behavior and abrasive wear resistance of multi-alloyed white cast irons with basic alloy composition in the heat-treated state. The chemical composition of the specimens is 2.00 – 2.40%C, 5% of Cr, Mo, W and V each, 2.0%Co and 0.00 – 2.58%Nb. On the heat treatment behavior, the relationship between hardness, volume fraction of retained austenite (V_γ) and tempering temperature in the different austenitizing temperatures will be clarified. The abrasive wear resistance will be evaluated using a Suga abrasive wear tester for two-body-type wear and a rubber wheel abrasive wear tester for three-body-type wear. Then correlation between hardness, V_γ , niobium content and abrasive wear resistance under different heat treatment conditions will be discussed.

1.3 The scopes of the thesis

1.3.1 Preparation of specimens with 2.0-2.4%C, 5% of Cr, Mo, W and V each, 2.0%Co and 0.0-2.58%Nb.

1.3.2 Heat treatment of annealing at 950°C, hardening from 1050°C and 1100°C and tempering at 400-600°C with 50°C intervals.

1.3.3 Observation of microstructure in the as-cast and the heat-treated states.

1.3.4 Measurement of macro-, micro-hardness and V_{γ} , abrasive wear resistance, heat treatment condition and Nb content.

1.3.5 Evaluation of abrasive wear resistance using Suga and rubber wheel abrasive wear tests.

1.3.6 Clarify correlation among hardness, V_{γ} , abrasive wear resistance, heat treatment condition and Nb content.

1.4 Expected results

1.4.1 The effect of niobium content on the heat treatment behavior and abrasive wear resistance of multi-alloyed white cast iron was clarified.

1.4.2 The correlations among niobium content, hardness, the volume fraction of retained austenite, and abrasive wear resistance of multi-alloyed white cast iron were revealed.

1.4.3 The results of this research provide a useful guideline for selecting suitable heat treatment to improve the abrasive wear resistance of multi-alloyed white cast iron.

1.5 The research places

1.5.1 Suranaree University of Technology's (SUT) Center for Scientific and Technological Equipment, Nakhon Ratchasima, Thailand.

1.5.2 Mahasarakham University's (MSU) Department of Manufacturing Engineering, Faculty of Engineering, Mahasarakham, Thailand.

1.5.3 National Institute of Technology-Kurume College's (NCT-Kurume) Department of Materials System Engineering, Fukuoka, Japan.