

CHAPTER V

CONCLUSION AND RECOMMENDATIONS

This study systematically investigated the influence of Nb on the microstructural evolution, hardness behavior and abrasive wear resistance of multi-alloyed white cast iron subjected to heat treatment. The multi-alloyed white cast irons with Nb contents varying from 0.00 to 2.58%, as well as a C from 2.00 to 2.40%, were produced. These specimens were subsequently annealed, hardened and tempered under various conditions. Furthermore, abrasive wear performance was evaluated using both the Suga abrasive wear test (two-body type) and the rubber wheel abrasive wear test (three-body type). The obtained results are summarized as follows:

5.1 Effect of Nb addition on solidification behavior

5.1.1 The as-cast microstructure consisted of primary austenite dendrites (γ_p) and the eutectics ($\gamma+MC$) and ($\gamma+M_2C$). At 1.05%Nb and above, primary MC carbides (MC_p) crystallized directly from the melt prior to the eutectic reactions, shifting the alloy from hypoeutectic to hypereutectic solidification.

5.1.2 Nb partitioned predominantly into MC-type carbides (both primary MC_p and eutectic MC), while its solubility in eutectic M_2C carbides and the matrix remained negligible.

5.1.3 The area fraction of eutectic MC carbide increased from the Nb-free specimen to a maximum at 0.70%Nb, then decreased sharply at 1.05%Nb and increased again. The area fraction of eutectic M_2C carbide decreased steadily with increasing Nb content. In the case of MC_p , the area fraction increased with increasing Nb from 1.05% to 2.58%.

5.1.4 The macro-hardness and micro-hardness in the as-cast condition increased up to 0.70%Nb, decreased to a minimum at 1.05%Nb and then increased with increasing Nb content.

5.2 Effect of Nb addition on heat treatment behavior

5.2.1 In as-hardened state

5.2.1.1 In the as-hardened condition, the matrix was composed of martensite, secondary carbides and retained austenite.

5.2.1.2 The area fraction of secondary carbide decreased with increasing Nb up to 1.05% and then increased.

5.2.1.3 As-hardened macro- and micro-hardness decreased to a minimum at 1.05%Nb, then recovered with increasing Nb content.

5.2.1.4 The V_γ in the as-hardened condition increased with increasing Nb content.

5.2.1.5 The higher austenitizing temperature consistently increased V_γ and decreased the area fraction of secondary carbide and the hardness for all Nb contents.

5.2.2 In tempered state

5.2.2.1 In the case of tempered specimens, all alloys displayed characteristic secondary hardening, caused by the precipitation of fine secondary carbides and the transformation of retained austenite into martensite.

5.2.2.2 The maximum tempered hardness (H_{Tmax}) was obtained at a tempering temperature of 525°C for both austenitizing temperatures.

5.2.2.3 The area fraction of secondary carbide in H_{Tmax} specimens decreased with increasing Nb content up to 1.05% and then increased.

5.2.2.4 Regardless of Nb content, the higher area fraction of secondary carbide and H_{Tmax} were obtained in specimens hardened from the higher austenitizing temperature.

5.2.2.5 With increasing Nb content, the macro- and micro-hardness of H_{Tmax} specimens decreased to the minimum value at 1.05%Nb and then increased. The highest H_{Tmax} was obtained in the 2.58%Nb specimens at both austenitizing temperatures with values of 907.1 HV30 and 817.5 HV0.1 for 1050°C austenitizing temperature and 927.0 HV30 and 854.7 HV0.1 for 1100°C austenitizing temperature.

5.2.2.6 The V_γ values in all H_{Tmax} specimens were consistently lower than 10%.

5.2.2.7 The degree of secondary hardening (ΔH_{sm}) reached its maximum at 0.70%Nb, dropped sharply at 1.05%Nb and increased again with further Nb addition. The higher austenitizing temperature produced a larger ΔH_{sm} regardless of the Nb content.

5.3 Effect of Nb addition on abrasive wear behavior

5.3.1 A linear relationship between wear loss (W_l) and wear distance (W_d) was obtained in both the Suga and rubber wheel abrasive wear tests. The wear rate (R_w), which was expressed as the slope of each straight line, varied depending on the Nb content and heat treatment conditions.

5.3.2 The Suga (two-body type) abrasive wear condition was approximately 27 times more severe than the rubber wheel (three-body type) condition, based on the specific wear rate comparison for the 2.58%Nb specimen, reflecting the higher cutting severity of fixed hard SiC abrasive relative to the freely moving, comparatively soft SiO₂ particles.

5.3.3 In the Suga abrasive wear test, the R_w on the As-hardened and H_{Tmax} specimens increased with Nb content up to 1.05%Nb and then decreased sharply in specimen No.4, which achieved the lowest R_w of all specimens owing to its higher hardness and larger carbide fraction.

5.3.4 In the rubber wheel test, however, R_w decreased with Nb content up to 1.05%Nb and then increased in 2.58%Nb specimen, because the larger and coarser MC_p carbides in the high-Nb, high-carbon alloy were more prone to losing matrix support, cracking and pull-out under three-body abrasion despite the higher matrix hardness.

5.3.5 Regardless of Nb content, specimens hardened from higher austenitizing temperature resulted in lower R_w values.

5.3.6 The As-hardened and H_{Tmax} conditions consistently gave lower R_w than the L-H_{Tmax} and H-H_{Tmax} conditions regardless of abrasive wear test, the Nb content and austenitizing temperatures.

5.3.7 In the case of two-body abrasive wear, the 2.58%Nb specimens provide the best wear resistance due to the increase in hardness by the crystallization of MC_p carbide, high amount of eutectic carbide and secondary carbide and high matrix hardness.

5.3.8 For three-body abrasive wear, the 1.05%Nb gave the best wear resistance because of a better balance between carbide size, distribution and matrix support.

5.3.9 In both wear tests and SEM observation of the worn surface consisted of scratching, grooving and pitting wear in all specimens. Additionally, the carbide pull-out was observed on the rubber wheel worn surface, occurring locally in the MC_p carbide regions.

5.3.10 Overall, the best abrasive wear resistance was governed by the combined effect of Nb content, heat treatment condition, matrix hardness, retained austenite fraction/stability and abrasive wear mode, rather than maximizing any single one of these factors.

5.4 Recommendations

5.4.1 The effect of varying carbon content at a fixed Nb level should be systematically investigated, since in the present study the highest-Nb specimen (2.58%Nb) also contains the highest carbon content simultaneously. A systematic C-Nb compositional design would allow the individual and interactive effects of both elements to be clarified.

5.4.2 Field or pilot-scale trials under actual service conditions (e.g., mill liners, crusher component) are recommended to validate the laboratory-scale Suga and rubber wheel wear test findings under real operating load, abrasive type and impact conditions.

5.4.3 Since this study focused solely on abrasive wear, future work should examine combined impact-abrasion loading, which is more representative of industrial applications such as crushing and grinding equipment.