The Journal of CPRI,
Vol. 9, No. 1, March 2013 pp. 169–176

Investigation of Mechanical Properties and wear behavior of Ni-alloyed Specially Heat Treated Permanent Moulded Austempered Ductile Iron (PMADI) for Power Plant Applications

Sethuram D* and Narasimha Murthy K**

Austempered ductile iron (ADI) is relatively newer material, which has attracted researchers and manufacturers alike mainly because of its immense properties and also at the same time cheaper to process and produce. Utilization of permanent moulds to ADI has many advantages such as very good dimensional stability, good nodule size count, better surface finish and environmental cleanness. Extensive literature survey reported that ADI out-performs proprietary abrasion resistant steels at similar bulk hardness levels.

Experiments were systematically planned to study the mechanical and wear properties of Ni-alloyed PMADI and are processed by a novel two step austempering process. All specimens were initially austenitized at 950 °C for 2 h. These samples were initially quenched for 5 min in a salt bath maintained at 250° C and then austempered for 2 h at several austempering temperatures. These temperatures were 280° C, 310° C, 340° C, 370° C, 400° C, and 430° C. The results show that this novel process has resulted in higher tensile strength, yield strength, hardness and wear resistance than the conventional single step austempering process. The tensile strength value improved by about 11% for 2% Ni PMADI samples over 1.5% i PMADI samples while maintaining reasonable levels of ductility. The results are analyzed based on the micro structural features.

Keywords: *Ni-alloyed austempered ductile iron, Two-step austempering process, Wear and Mechanical properties.*

1.0 INTRODUCTION

Austempered ductile iron (ADI) belongs to the family of cast iron. ADI has excellent characteristics of strength, toughness and wear resistance. It is being used increasingly in engineering application, especially in the power and mining industries. Hubs and frames of wind turbines are made of Ductile iron [1]. Components used in coal handling equipments such as chutes and liners in power plant components are made of ADI [2].

Austempered Ductile Castings for technologically advanced centrifugal and reciprocal compressors along with steam and gas turbines. Applications include crankcases, rotor casings, inlet covers, outlet covers and slide valves [3]. Connecting rods, crank shafts, differential gears are made of ADI is replacing steel forgings and castings with its excellent properties and relatively low manufacturing cost. Conventionally, ADI is cast in sand moulds. However, utilization of permanent molds to produce ADI has several advantages in terms of finer graphite nodules, good surface

*Department of Mechanical Engineering, PES Institute of Technology, Bangalore - 560 085. E-mail: sethurampesit@yahoo.co.in.
**Principal, Sri Krishna School of Engg. and Management, Bangalore - 560 035. E-mail: murthykn59@gmail.com.

finish and repeatability of castings, dimensional accuracy and environmental cleanliness. Here, the presence of appreciable amounts of retained austenite in ADI leads to better wear resistance and fatigue strength, due to the high work-hardening nature of the austenite. Considerable work has been reported in understanding the micro structural characteristics of a number of ADIs and their effect on tensile properties, impact toughness and fracture toughness.

Seetharamu *et al.* [4] have reported beneficial effects of utilizing permanent moulds to produce ADI. The reported results have indicated that there is an improvement in the mechanical and tribological properties of ADI produced from permanent moulds as compared to ADI produced from sand moulds.

Murthy *et al.* [5] have reported improved wear and mechanical properties of permanent moulded ADI with Mn as an alloying element. The wear and mechanical properties of ADI are dependent on the matrix microstructure which consists of bainite and retained austenite. The austenite phase in the matrix accommodates higher strain before yielding and hence enhances wear behavior of ADI. Several researchers have employed various heat treatment methods to achieve improved wear resistance and mechanical properties of ADI.

Putatunda *et al.* [6] have successfully developed a novel two-step austempering process on ADI. Effect of this special heat treatment on microstructure and mechanical properties of the material have been examined. Test results have shown a significant improvement in mechanical properties and fracture toughness of the material as a result of two-step austempering process. Improved fracture toughness characteristics of ADI produced by two-step austempering process have also been reported by Ayman *et al*. [7]. He has studied the fracture toughness of ADI by both conventional and two-step austempering processes and resulted in improving the fracture toughness of the material, while maintaining the reasonable levels of strength. Also, alloying of ADI with Ni and Mo increased its tensile strength and hardness.

Gaston *et al.* [8], studied the effect of new two-step austempering heat treatment process, developed by Putatunda, on mechanical properties with emphasis on the response to the abrasive behavior. Results show better wear resistance for two-step ADI in comparison with conventional ADI. Alloying elements like Ni and Mn have beneficial effects on structure and properties of ADI. Gundlach [9] has emphasized the use of Mn as potential austenite stabilizer to provide increased hardanability. Gagne [10] has reported the wide range of mechanical properties in ADI with varied Mn levels. Nili Ahmadabadi *et al.* [11] has reported that increase in the Mn content not only delays the stage of bainitic reaction, but also delays stage two transformations.

O Eric *et al.* [12] have studied the effect of austempering heat treatment on the microstructure and toughness of nodular cast iron alloyed with Mo, Cu, Ni and Mn. The results shows that for specimens austempered at 320° C, toughness steeply increases to a maximum of 115 kJ after 2.5 h of austempering. With the longer time of austempering, toughness decreases to a level between 85–90 kJ. Test samples austempered at 400° C showed very low values of impact energy (10 to 12 kJ) from 0.5–5 h of austempering. Kovacs [13] has reported that Ni increases impact toughness. Ni has the ability to stop the precipitation of secondary carbides in the upper bainitic range. The demand for an alternative material to replace costly steels for various applications is now becoming a reality. Jianghuai Yang *et al.* [14] have also carried out investigations to examine the influence of two-step austempering process on the strain hardening behavior of ADI.

Research findings have shown that two-step process resulted in improved micro structural variables in the ADI matrix and higher yield and tensile strengths and lower ductility and strain values exponent compared to conventional austempering process. Yoon-Jun Kim *et al.* [15] have investigated into mechanical properties of ADI in accordance with austempering temperature. Here, samples were alloyed with Cu and

Molybdenum and austempered over a temperature range from 350° C–410° C. Results have shown that the tensile strength was highest for 350° C. Cu and Mo additions have played effective role in the formation of ausferritic structure as well as improvement of mechanical properties such as tensile strength and haredenablility. A detailed review of the literature indicates that there is an improvement in wear and mechanical properties of ADI subjected to two-step austempering process.

However there is less published information on the role of alloying elements like Ni, Mn and Cu on the structure and properties of permanent molded ADI subjected to two-step austempering heat treatment process. Thus, experiments are systematically planned to develop PMADI subjected to novel two-step austempering heat treatment which will have excellent wear and mechanical properties and to study the morphology of bainite and its effect on mechanical properties like tensile strength, toughness and wear resistance.

The present work is focused on the investigation of mechanical properties and wear behavior of PMADI alloyed with Ni and is subjected to novel two-step austempering heat treatment process. The results are analyzed based on graphite morphology and Bainitic matrix.

2.0 EXPERIMENTAL PROCEDURE

2.1 Melting and casting

Ductile iron castings alloyed with Ni were melted in coreless induction furnace of 15 kg capacity. The charge materials used were clean mild steel scrap, petroleum coke and ferro-silicon alloy. The melt was super-heated to 1500°C and treated with ferro-silicon magnesium alloy and post inoculated using ferro-silicon (inoculation grade) and stirred well prior to pouring. The melt was poured at 1400° C–1425° C into a pre-heated (200° C) gray cast iron permanent mould after deslagging. The permanent mould employed in this work is shown in Figure 1.

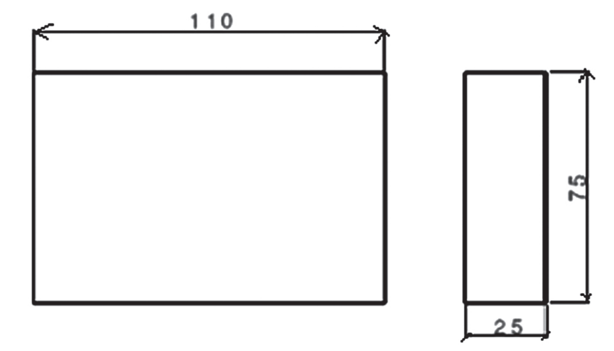

FIG. 1 PERMANENT MOULD SPECIFICATION.

Nickel additions were made to the melt in different levels (0.5%, 1%, 1.5%, 2%, and 2.5%). The chemical composition (wt. %) of the castings poured are shown in Table 1.

TABLE 1

NOMINAL COMPOSITION (WT. %) OF Ni-ALLOYED PMADI SAMPLES

Casting designation	C	Si	Ni	S	Mg
0.5 Ni PMADI	3.32	2.94	0.52	0.03	0.04
1 Ni PMADI	3.26	2.87	1.08	0.03	0.04
1.5 Ni PMADI	3.31	2.90	1.54	0.03	0.04
2 Ni PMADI	3.34	2.92	2.02	0.03	0.04
2.5 Ni PMADI	3.29	2.93	2.56	0.03	0.04

2.2 Special two-step austempering heat treatment

The test samples were also initially austenitized at 950° C for 2 h and then quickly quenched into molten salt bath maintained at 250° C for 5 min to obtain sufficient super cooling and nucleation of ferrite. Immediately after that, the samples were transferred to another salt bath which was maintained at predetermined austempering temperatures, such as: 280° C, 310° C, 340° C, 370° C, 400° C, and 430° C. The samples were austempered at these temperatures for 2 h and finally air cooled.

Two-step austempering heat treatment cycle employed is as shown in Figure 2.

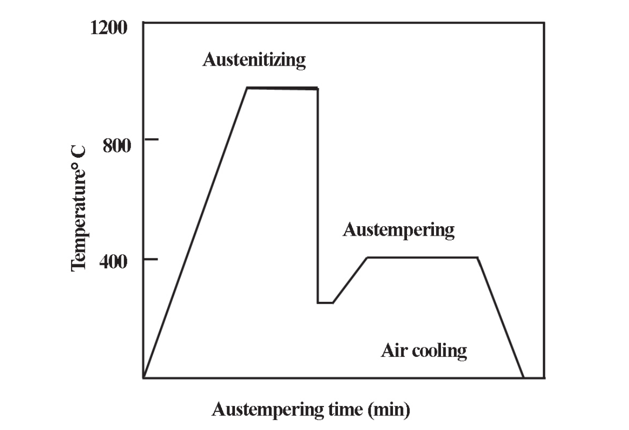

FIG. 2 TWO-STEP AUSTEMPERING HEAT TREATMENT CYCLE.

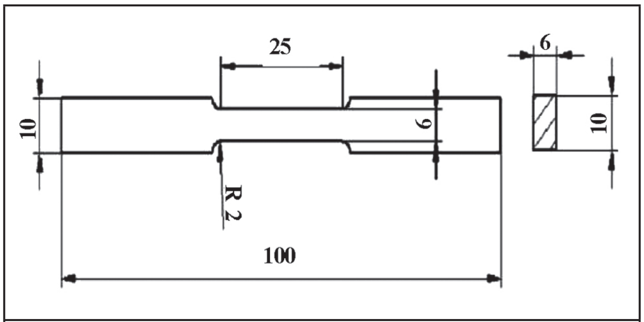

FIG. 3 TENSILE TEST SPECIMEN.

2.3 Microstructure

The microstructure of the as-cast Ni-alloyed samples and specially heat treated samples were examined under an optical microscope. The fractured samples were examined using scanning electron microscope.

2.4 Tensile Test

The tensile properties of PMADI samples for ultimate tensile strength and ductility (% elongation) were evaluated using Japan servo pulsar-servo hydraulic dynamic testing machine. The test was carried out as per ASTM standard E from specifications. The machined tensile test samples was held with suitable grips between the cross yoke and the actuator of the machine. Uni-axial load at a uniform rate was applied on the test samples through the actuator until it failed. The variation of applied load Vs the displacement was recorded using X–Y recorder. The tensile strength and % elongation were determined. The average of three measurements were recorded and reported. Tensile test specimen is as shown in Figure 3.

2.5 Hardness Test

Hardness testing was performed using Vickers hardness tester with applied load of 20 kg-f according to ASTM E92-82. Five readings were taken for each specimen and the results were averaged.

2.6 Rubber Wheel Abrasion Test

The test specimen of size 75 mm × 25 mm × 6 mm was made flat on either surface by grinding it on belt emery and the test was carried out as per ASTM G76 standards. The test equipment consists of a wheel with rubber beading around the circumferential periphery of the wheel. Test samples were suitably held in the specimen holder and were held in position against the rubber wheel by means of lever arrangement. The rubber wheel was rotated and the pressure was applied by means of loads suspended over the lever arrangement. Sand at a constant flow rate held in the top of the reservoir was allowed to fall between the rotating rubber wheel and the specimen through a nozzle. The test was conducted for 30 min or 6000 revolutions of the rubber wheel, which was rotated at 200 rpm. The rubbing of the abrasive sand particles against the test samples lead to physical wear of samples. The initial and final weights of the test samples before and after the test respectively were measured.

3.0 RESULTS AND DISCUSSIONS

3.1 Microstructure

It is observed that for the samples austempered in the range of 310° C–340° C long bainitic fibres were observed. As the austempering temperature increases (temperature range of 340° C–370° C) the bainitic fibres appears shorter and finer and equally distributed. Further increase in the austempering temperature (temperature range of 370° C–400° C) the bainite appears scattered with carbides present in the matrix. Representative microstructure photographs and SEM photographs are shown in Figures 4–9.

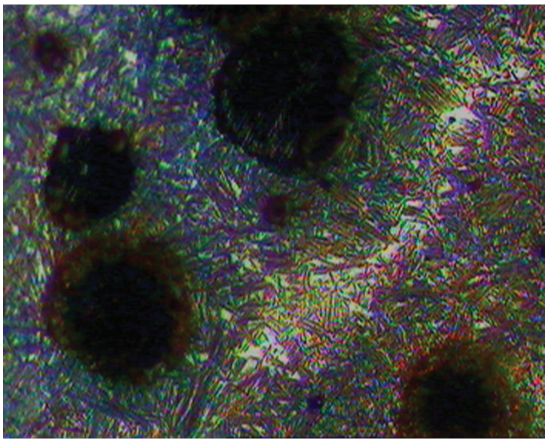

FIG. 4 MICROSTRUCTURE OF PMADI 1.5% Ni SAMPLES AUSTEMPERED AT 340^{O} C (100X-NITAL ETCHED).

3.2 Tensile Strength

Figures 10–11 shows results for the tensile strength measurements and the % elongation of Ni-alloyed PMADI samples subjected to two-step heat treatment. It is evident from the data presented in the graph that the tensile strength value improved by 11% for 2% Ni PMADI samples over 1.5% Ni PMADI samples. There was 9% reduction in the tensile strength of 2.5% Ni PMADI samples compared to 2% Ni PMADI samples. Hardness variation with two-step austempering temp. and % Ni is shown in Figure 12. The higher the austempering temperature used in the heat treatment, lower the yield and ultimate strength and the higher the ductility.

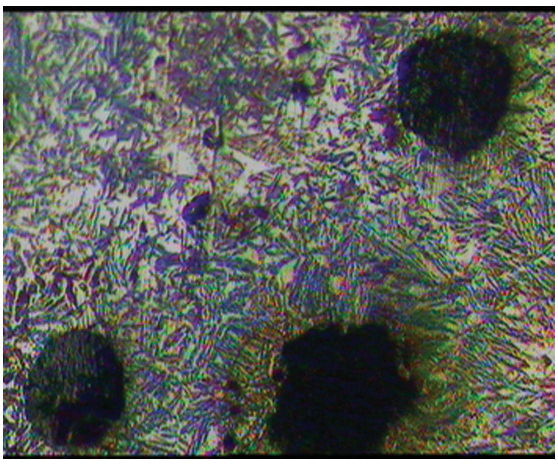

FIG. 5 MICROSTRUCTURE OF PMADI 2.0% Ni SAMPLES AUSTEMPERED AT 340^{O} C (100X-NITAL ETCHED).

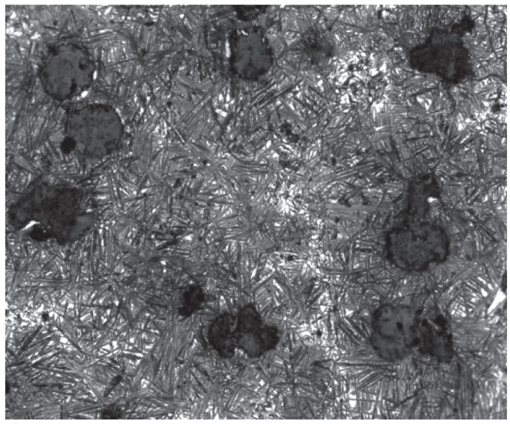

FIG. 6 MICROSTRUCTURE OF PMADI 2.5% Ni SAMPLES AUSTEMPERED AT 340^{O} C (100X-NITAL ETCHED).

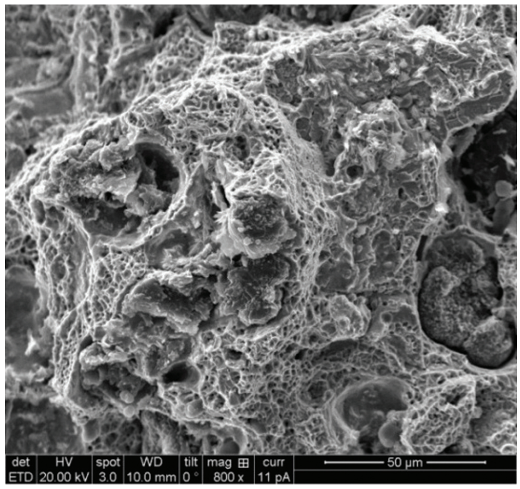

FIG. 7 SEM PHOTOGRAPH OF FRACTURED PMADI 1.5% Ni TENSILE SAMPLES AUSTEMPERED AT 340^{O} C.

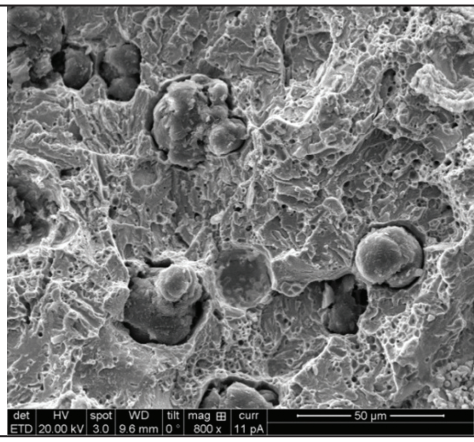

FIG. 8 SEM PHOTOGRAPH OF FRACTURED PMADI 2.0% Ni TENSILE SAMPLES AUSTEMPERED AT 340^{O} C.

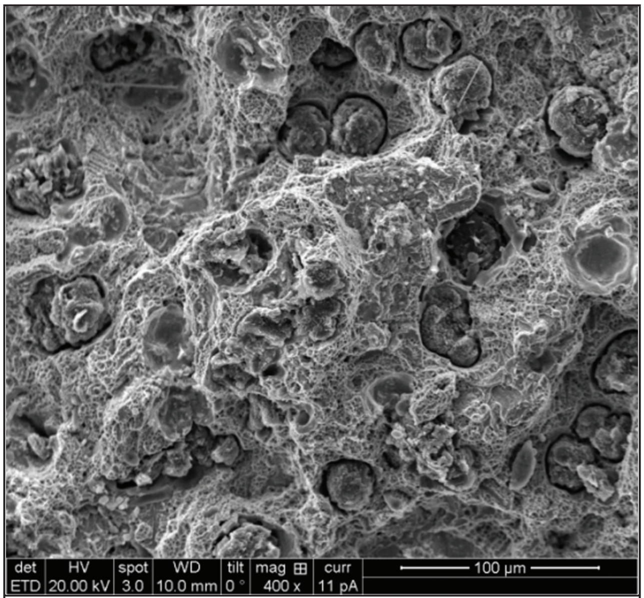

FIG. 9 SEM PHOTOGRAPH OF FRACTURED PMADI 2.5% Ni TENSILE SAMPLES AUSTEMPERED AT 340^{O} C.

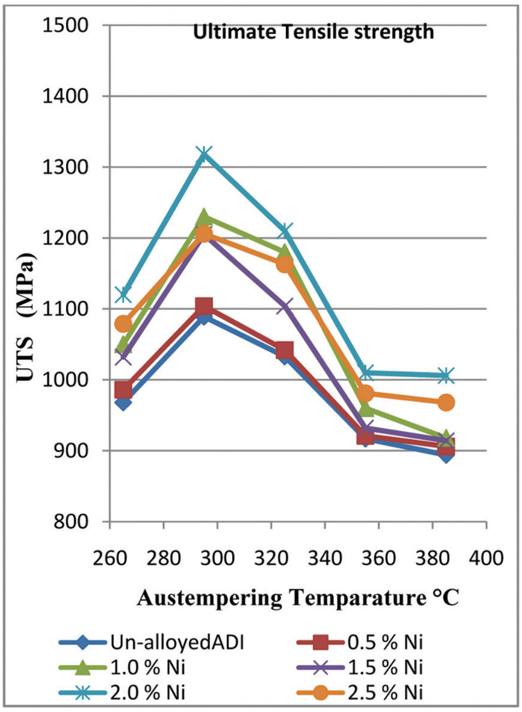

FIG. 10 TENSILE STRENGTH VARIATION WITH TWO-STEP AUSTEMPERING TEMP. AND % Ni.

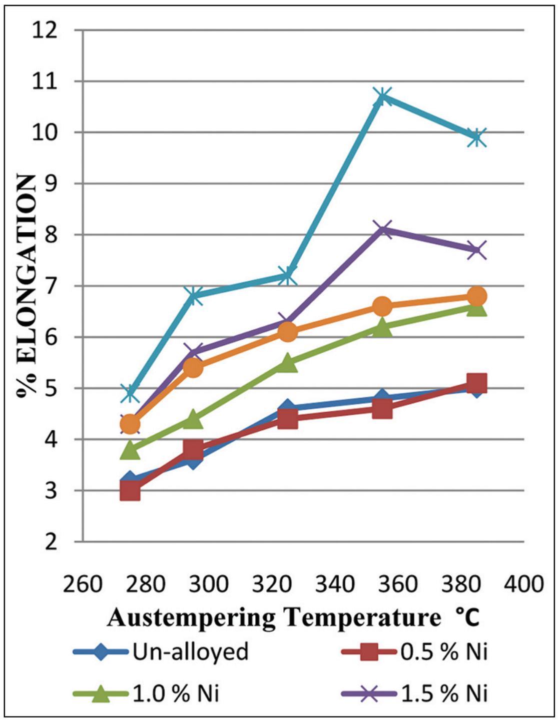

FIG. 11 % ELONGATION VARIATION WITH TWO-AUSTEMPERING TEMP. AND % Ni.

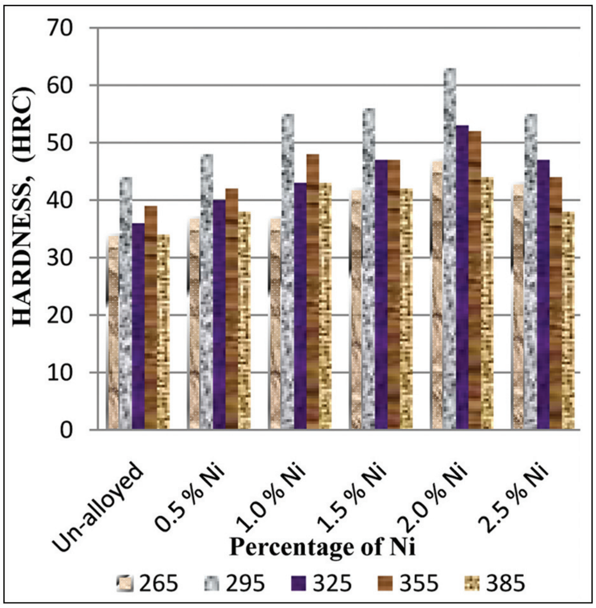

FIG. 12 HARDNESS VARIATION WITH TWO-STEP AUSTEMPERING TEMP. AND % Ni.

It is also evident from experimental results that two-step austempering has the advantage of gaining higher yield and ultimate strength levels while maintaining the reasonable levels of ductility. Similar trend observed with hardness and ductility also. The advantage can be attributed to the smaller grain size of bainitic ferrite and austenite that lead to higher yield and ultimate strength. Ductility is also improved for two-step process, at higher austempering temperature. This may be due to increased diffusion rate of carbon from ferrite to austenite. Two step process has resulted in lower ductility than the single step process. This reduction in ductility may be due to the general trend of decreasing ductility as the strength increases. ADI alloyed with Ni improved strength levels and wear resistance up to 2% Ni and later it is showing decreasing trend.

3.3 Rubber Wheel Abrasion

The results of the rubber wheel abrasion test is represented in the Figure 13. PMADI samples heat treated by novel two step heat treatment process has shown 16–18% improvement in the abrasion resistance compared to samples subjected to conventional austempering heat treatment and is maximum in the austempering temperature range 300° C–350° C.

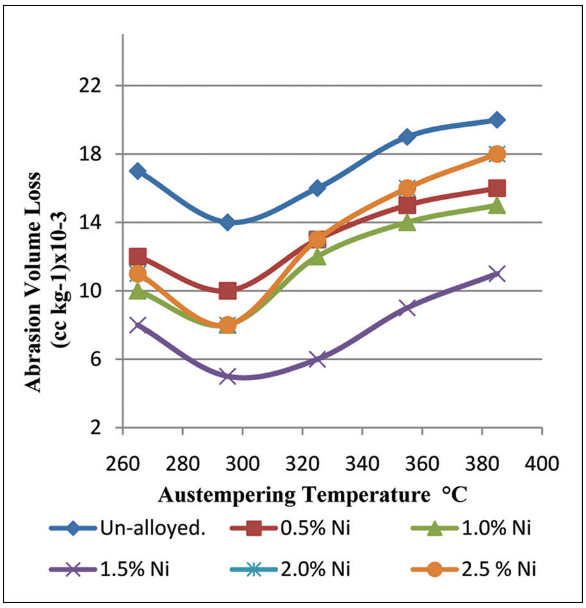

FIG. 13 RUBBER WHEEL ABRASION VOLUME LOSS WITH TWO-STEP AUSTEMPERING TEMP AND % OF Ni.

4.0 CONCLUSIONS

ADI processed using two-step austempering method is found to possesses enhanced strength and wear characteristics when compared to conventional ADI. This material could replace components such as crankcases, rotor casings, inlet covers, hubs and frames used for wind turbines and thermal power plant applications.

The tensile strength value improved by about 11% for 2% Ni PMADI samples over 1.5% Ni PMADI samples while maintaining reasonable levels of ductility. There was about 9% reduction in the tensile strength of 2.5% Ni PMADI samples compared to 2% Ni PMADI samples.

The two-step process has resulted in higher tensile strength, yield strength, hardness and wear resistance than the conventional single step austempering process. Test samples resulted in good nodular count and size. Finer austenite and ferrite as well as higher austenitic carbon in the matrix may be accountable for the improvement in the wear and mechanical properties. Test samples show substantial improvement in abrasion resistance when compared to samples subjected to conventional austempering heat treatment. It is found to be maximum in the austempering temperature range 300–350° C.

ACKNOWLEDGEMENT

The authors wish to thank PES Institute of technology for the support and cooperation rendered in successful completion of the research work.

REFERENCES

[1] Roedter H. "Powerful Ductile Iron - castings for power plants and wind energy applications", *Sorelmetal Technical Serivices*.

[2] Uma T R, Simha J B,Narasimha Murthy K. "Influence of nickel on mechanical and slurry erosive wear behaviour of permanent moulded toughened austempered ductile iron." Wear, No. 271, pp. 1378–1384.

[3] Martinez R, Boeri R and Sikora J. "Impact and fracture properties of ADI, comparison with 4140 steel", *American Foundrymens*

Society Congress, Vol. 98, No. 008, 1998.

[4] Seetharamu S, Sampathkumaran P, Kumar R K, Narasimha Murthy K and Martin Jebraj P. "Abrasion and erosion resistance of permanent moulded austempered ductile iron", Wear, No. 167, 1–8, 1993.

[5] Narasimha Murthy K, Sampathkumaran P and Seetharamu S. "Abrasion and erosion behaviour of manganese alloyed permanent moulded austempered ductile iron", Wear, No. 267, pp. 1393–1398, 2009.

[6] Putatunda S. "Development of austempered ductile iron with simultaneous high yield strength and fracture toughness by a novel novel two-step austempering process." *Mater Sci Eng.*, No. 315, pp. 70–80, 2001.

[7] Ayman H Elsayed, Megahed M M, Sadek A A and Abouelela K M. "Fracture toughness characterization of ADI produced using both conventional and two-step austempering process", *Materials and Design*, No. 30, pp. 1866–1877, 2009.

[8] Francucci G, Sikora J and Dommarco R. "Abrasion resistance of ductile iron austempered by the two-step process", *Materials Science and Engineering,* No. 485, pp. 46–54, 2008.

[9] Dodd G and Cast Metals Development Ltd. "Austempered ductile iron castings-advantages, productions, properties and specifications", *Materials and Design,* Vol. 13, 1992.

[10] Gagne M. "The influence of Manganese and Silicon on the microstructure and tensile properties of austempered ductile iron", *Trans. A.F.S.* No. 93, pp. 108, 1985.

[11] Nili A M, Ghasemi H M, Osia M. 'Wear', No. 231, pp. 293–300, 1999.

[12] Erica O, Sidjaninb L, Miskovica Z, Zeca S and Jovanovica M T. "Microstructure and toughness of CuNiMo austempered uctile iron", *Materials Letters*, Vol. 58, pp. 2707–2711, 2004.

[13] Kovacs B V. Mod. Cast., Vol. 36, pp. 38–41, 1990.

[14] Yang J and Susil K Putatunda. "Influence of novel two-step austempering process on the strain hardening behaviour of ADI", Department of Chemical Engineering and Material Science, Detroit, 2004.

[15] Kim Y J, Shin H, Park H and Lim J D. "Investigation into mechanical properties of austempered ductile iron (ADI) in accordance with austempering temperature", *Materials Letters*, Vol. 62, pp. 357–360, 2008.