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Effect of Prolonged Time Interval Between Quenching and Tempering on Hardness Profile Of 140mm Forged Steel Mill Balls:

A Case of ME Longteng Grinding Media (Zambia) Limited Factory, Kalumbila, Northwestern Province, Zambia

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By: Gregory Musonda Phiri
Department of Design and Technology
School of Engineering
Information and Communication University
Lusaka, Zambia
mpgreg2012@gmail.com

Mr. Moses Kaleji
Lecturer
School of Engineering
Information and Communication University
Lusaka, Zambia
moseskaleji@gmail.com

Abstract— *This paper outlines an experiment that was undertaken to study the effect of various time intervals between quenching and tempering on the hardness profile of 140mm forged steel mill balls manufactured by ME Longteng Grinding Media (Zambia) Limited (MELTZ). The investigation simulated conditions that prevail when power outage occurs. Six mill balls that were austenised, quenched and enrooted to the tempering furnace were used. Two of the balls, which were used as standards, were allowed to proceed with the tempering process with no time interference. Then one of each of the remaining four balls were held back and made to proceed with the process after two, Four, Six and twelve hours respectively. Hardness profile testing and examination of internal structure of each ball sample was then conducted. The results obtained showed that prolonged time interval between quenching and tempering caused by power outage had a slight negative effect on the hardness profile of the 140mm forged steel mill balls. The deterioration experienced, however, still left the product to be within the targeted acceptable quality limits and could be used in industry with negligible negative effect. It was recommended that multiple tests, metallography examination, as well as drop ball tests be conducted on such samples in order to conclusively ascertain the suitability of such balls in industry.*

KEYWORDS*: Forged Steel Mill Balls, Quenching, Tempering, Hardness Profile.*

I. CHAPTER ONE

1.0 INTRODUCTION AND BACKGROUND

This paper outlines an investigation that was carried out to determine the effect of prolonged time intervals between quenching and tempering on the hardness profile of 140mm forged steel mill balls manufactured by ME Longteng Grinding Media (Zambia) Limited (MELTZ) factory. The investigation was a simulation of a condition that exists on mill balls that would be between the quenching and tempering stages when there was power outage. Quenching is a hardening heat treatment conducted on austenised steel components while tempering is a stress relieving process conducted on quenched steel products. Tempering also increases ductility and toughness (Anon, 2015)

Most steel components used for various purposes normally undergo heat treatment after they have been shaped. The heat treatment is done to induce desired properties like stiffness, ductility, strength and toughness. In general, Heat treatment consists of timed heating and cooling of components (Anon, 2015).

In the case of forged steel mill balls, the most desired properties are hardness with minimal brittleness. Forged steel Mill balls that are used world-wide in mineral and cement processing plants to grind ore must have these properties to perform their duty. To achieve this, the shaped (forged) balls undergo an optimised heat treatment process that starts with austenisation. The balls are then quenched and this process is thereafter followed by tempering. As the balls go through these stages, great attention is paid to the time taken and the temperatures reached because Heat treatment mainly consists of timed heating and cooling of components (Tan, 2007).

In the process of austenisation, the component is heated to an austenised state. The temperature to reach this state is dependent on the carbon and alloying elements content and can be estimated from the Carbon – iron Carbide phase diagram. The component is then held at this temperature (soaked) for a period of time that is dependent on among other factors, the thickness of the component.

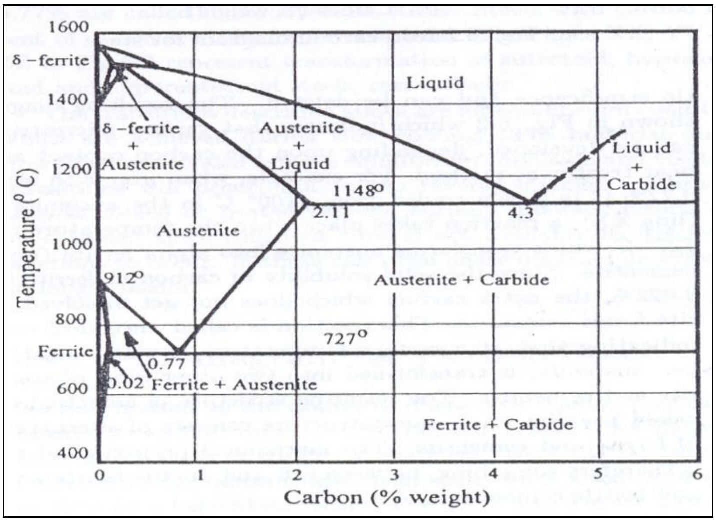

Fig. 1: Iron-Carbon Phase Diagram (Source: http://panit.iid.ac.in/-pmpandey)

Fig. 1 shows the Iron – carbon phase diagram. The X-Axis shows the Carbon content while the Y-Axis shows the temperature. Steels are up to a carbon content of about 2.11% while cast irons are obtained between 2.11% and 6.0 % carbon. Hypo eutectoid steels are obtained up to 0.77% carbon while

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Hypereutectoid steels are obtained with a carbon content that is between 0.77% and 2.11%. Out of this phase diagram, the various phases obtained at a given temperature for specified carbon content can be estimated.

The austenite state component is then quickly cooled. The media used for cooling can be water, brine, oil or forced air. This cooling action is called quenching. The structure targeted when quenching an austenised steel component is mostly martensite. This structure, for a particular steel alloy, is the hardest and strongest for any steel alloy, but in addition to that, it is the most brittle due to internal stresses that arise from the quenching process (Tan, 2007).

The tempering process is then used to relieve the internal stresses as well as to impart some ductility and some toughness on the quenched component.

As much as a component's thickness and chemical composition influences the microstructure and the resultant properties during heat treatment, it must be emphasised that the process is highly dependent on time and temperatures used.

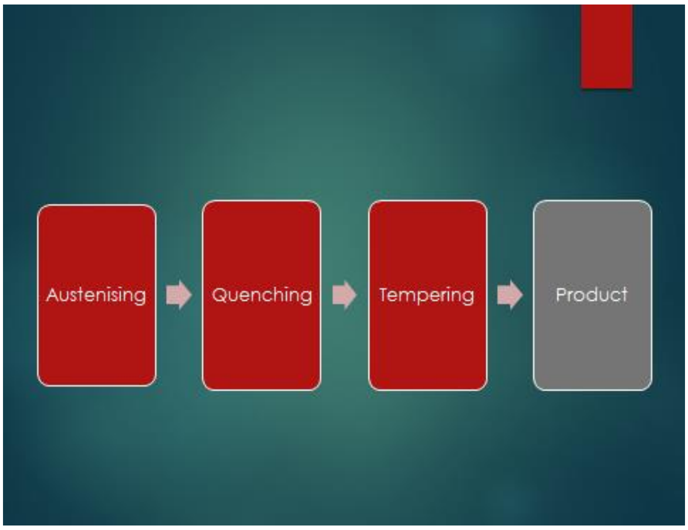

Fig. 2: Hardening Heat Treatment stages (Source: Author)

Fig. 2 above shows a schematic flowsheet of the hardening process where an austenised component is quenched. This is then followed by tempering.

It must be noted that the duration between the heat treatment stages can also affect the process and the product quality (Singh, Chhabra & Kapoor, 2017).

For example, a prolonged time between austenisation and quenching may result in the component being air cooled to a certain temperature (quenching temperature) before it is quenched. Similarly, the period between quenching and tempering may influence the temperature at which the component starts the tempering process and this, in turn, may influence the characteristics of a produced component. Thus, an alteration in time, during the heat treatment process, is certainly bound to affect the product.

At MELTZ, an alteration in time and temperatures on various stages is experienced, mostly when there is power outage

1.1. Statement of the Problem

In manufacturing heat treated forged steel products, the process is normally optimised in terms of the temperatures and the time taken during and between the various heat treatment stages (Singh, Chhabra & Kapoor, 2017). During production, the optimised conditions are adhered to in order to obtain products of a consistent desired quality.

MELTZ, a factory that started manufacturing forged steel Mill Balls in October 2018 uses raw material that is of a consistent quality and has optimised its heat treatment process to obtain very high-quality mill balls that yield high hardness profiles. The factory, however, faces a challenge of power outage that sometimes occurs without notice. When power outage occurs, the optimised periods between and during various stages, are disturbed. The process is forced to hold balls at various points for prolonged periods until power is restored. This includes balls that would have been quenched and are enrooted to tempering. The time it takes to restore power varies. For this reason, there was need to investigate the effect that this time interval has on the hardness profile, if the balls are allowed to proceed with the process.

1.2. Objective

The main objective of this research was to determine the effect that various time intervals between quenching and tempering has on the hardness profile of the 140mm forged steel mill balls manufactured at MELTZ in Kalumbila, Zambia.

The specific objectives of the study were to

i) Determine the hardness profile of the investigated samples.

ii) Examine the internal of the investigated samples in order to assess the grain size and the presence of any deformities by visual examination and Non-Destructive testing.

iii) Assess the strength of these samples through Drop ball tests and

iv) Asses the internal microstructure of the produced samples using metallographic examination.

1.3. Significance of the Study

The project was necessitated by the fact that there is an unexpected condition that sometimes, imposes itself on an optimised process at MELTZ – the power outage. This situation is unique and the effect on the process needed to be investigated. Time intervals between heat treatment processes are normally intentionally arrived at based on available literature, experience and optimisation tests. The process at MELTZ, however, finds itself to deal with an unintentional time period that is forced on it by power outage. With this, there was need to generate experimental information on which decisions on how to deal with such balls may be based.

The choice of using hardness test profile as the main means of assessing the effect of prior-to-quenching time intervals was arrived at because, hardness can be used to estimate the strength of a material (Tan, 2007).

1.4. Limitations

It must be noted that the researcher recognised the need to conduct multiple tests to firm up indications arrived at in this project. The project was, however, restricted by the competing need of using the same sample preparation and testing equipment for the company's production process. It is hoped that more tests can be conducted in future to explore this area.

It was also recognised that there may be need to extend the investigation to balls that may be held up in the tempering furnace when there was power outage. To simulate this, there would be need to hold balls in the tempering furnace for various periods. This was, however, not practical as it would hold and disturb the whole production process. This, however, can also be investigated in subsequent future power outages.

II. CHAPTER TWO

2.0 MATERIALS/METHODS

2.1 Overview

In seeking to investigate the effect of prolonged time interval between quenching and tempering on hardness profile of forged steel mill balls at MELTZ factory, experimental research method was used.

The investigation was an experiment that simulates conditions that prevail when power outage occurs at the time the mill balls are between quenching and tempering during the heat treatment process.

2.2 Materials/Equipment

2.2.1 Materials

Materials used in the project were as follows:

2.2.1.1 Samples

Six 140mm forged steel mill balls that were austenised, quenched and enrooted to tempering were used. These were sampled from the batch that was being processed for the day's production so as to ensure that all prior to quenching and tempering conditions were simulated to the normal production process. Two were used as standards while the other four were used to cover a testing period of twelve hours with each being held for a period of two,

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four, six and twelve hours, respectively, before being tempered. It was not possible to get more samples for multiple tests due to the competing need of using the same equipment production purposes.

2.2.1.2 Non-Destructive Testing (NDT) Consumables

One tin each of Penetrant, Penetrant Remover and Developer was used. The NDT method used required penetrant to be applied and the penetrant remover to remove the excess penetrant after the dwelling time and before applying the developer.

2.2.2 Equipment

Equipment used in the project was as follows:

2.2.2.1 Infrared Thermocouple

For measuring the temperature of the sampled balls

2.2.2.2 Mass Balance/Scale

For weighing the sampled balls

2.2.2.3 Vernier Caliper

Used for measuring the Ball diameters.

2.2.2.4 Electrical Discharge Wire Cutting Machine (EDM)

For cutting the 11mm thick semi-circle pieces from the ball samples

2.2.2.5 Polishing /Grinding Wheel

For polishing the 11mm thick semi-circle pieces from the ball samples

2.2.2.6 HRC 150 Hardness Testing Machine

For Hardness testing of the 11mm thick semi-circle pieces from the ball samples

2.2.2.7 Hydraulic Press

For splitting open the sampled balls for internal examination.

2.2.2.8 Austenising Furnace

For heating the forged Steel mill balls to austenite phase.

2.2.2.9 Quench Ponds

For quenching austenised forged steel mill balls.

2.2.2.10 Tempering Furnace

For heating (tempering) the quenched Steel mill balls

2.3 Method

Six forged steel mill balls that were austenised, quenched and enroute to the tempering furnace along with the bulk of the production process balls were sampled. Two of the balls, which were used as control or standard samples, were made to proceed with the tempering process with no time interference i.e. One at the beginning of the investigation process and another at the end. In order to simulate power outage, the sampled balls were kept at room temperature atmosphere within the vicinity between the quenching pond and tempering furnace.

One of each of the remaining four balls were held back and made to proceed with the process after two, Four, Six and twelve hours respectively. The temperature of the sampled balls was taken on an hourly basis up to the time they were made to proceed with the tempering process.

Each of the timed samples was then collected after tempering, weighed and the diameter measured before a semi-circle 11mm thick piece was cut and prepared for hardness profile testing. An Electric Discharge Wire cutting Machine (EDWM cutter) was used to cut the sample.

Fig. 3: Picture of an EDM Cutting Machine. (SOURCE: Author)

Fig. 3 shows a complete set up of an EDM cutting machine connected to one of the computers (Left side). The other computer is for the next EDM cutting machine (not in picture).

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Fig. 4: Picture of an EDM Cutting Machine Computer Monitor. (SOURCE: Author)

Fig. 4 shows an EDM cutting machine computer monitor on which the cutting path of the cutter can be seen.

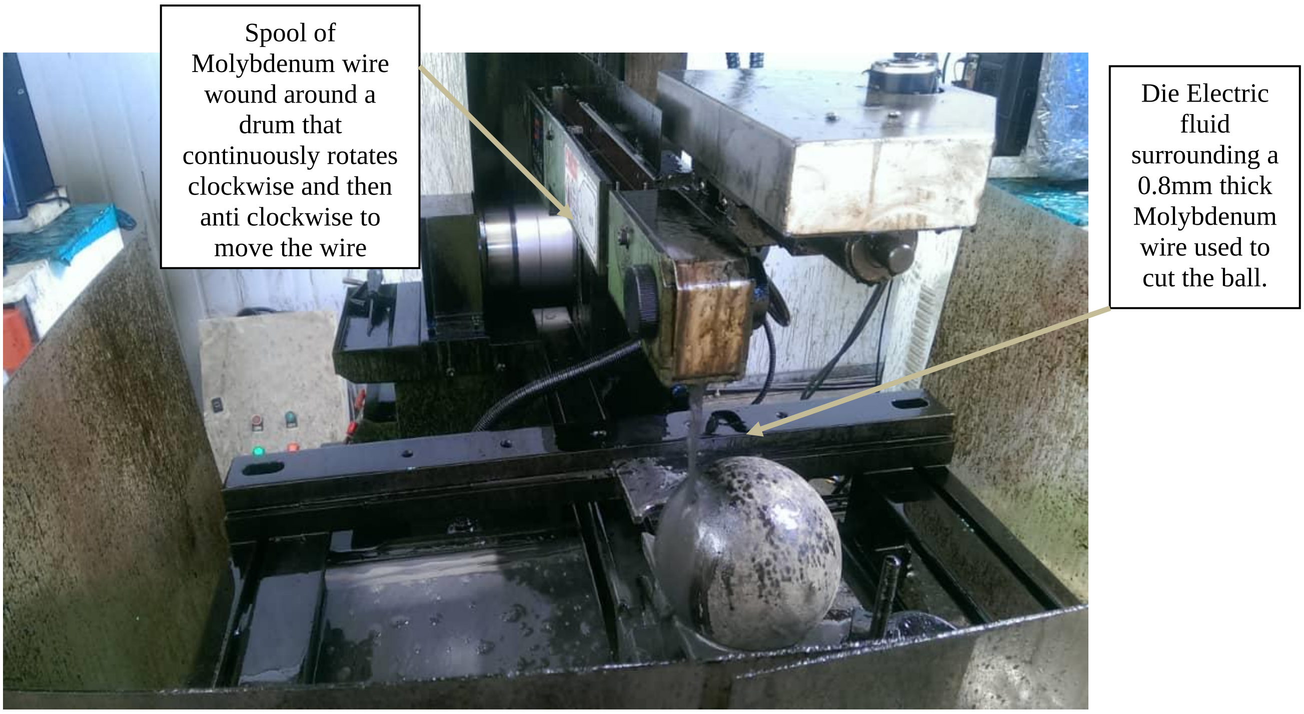

Fig. 5: Picture of a Mill Ball Sample Being Cut on an EDM Cutting Machine (SOURCE: Author)

Fig. 5 shows an EDM machine cutting a sample from a heat-treated forged mill ball for Hardness Testing.

Fig. 6: Picture of an EDM Cut Sample in the cut Slot (SOURCE: Author)

Fig. 6 shows an 11mm thick semi-circle sample placed in the slot from which it was cut using an EDM Wire cutting machine.

Fig. 7: Hardness Tested Points on EDM Cut and Polished Sample (SOURCE: Author)

Fig. 7 shows hardness tested points on a polished sample that was cut using an EDM cutting machine. The first three adjacent points from the surfaces were tested at a distance of 3mm from the ball surface (curved side) while the rest were tested at equal incremental distances of 5mm i.e. 8mm, 13mm, 18mm, ……………..68mm, towards the centre of the ball.

Each of the remaining pieces, after cutting the hardness profile sample, was then split open using a hydraulic press ball breaker for macro visual examination. The 11mm thick pieces and the split pieces were also subjected to Non-destructive tests (NDT). The initial plan was to sample similar timed balls for Drop ball tests. This was, however, not done due to the priority of testing production samples instead of the project samples.

To measure the hardness, a line was drawn from the centre to the circumference of each of the semi-circle 11mm thick samples that were cut using an EDM cutter. The line was marked at 3mm from the circumference and then followed with equal intervals of 5mm each up to the centre. It is on these markings that three, side-by-side hardness measurements were taken. An HRC 150 hardness testing machine was used.

For Non-Destructive Tests, Liquid Penetrant test was conducted instead of the recommended Magnetic particle Inspection for ferrous material. This was due to the non- availability of a Magnetic Yoke. Precautions were however taken to ensure that results were indicative by using the same method on a sample that had flaws where the flaws were detected very clearly.

Drop ball test was not done due to the above stated reason while Metallography examination was yet to be conducted.

The results obtained were assessed and recommendations made. The researcher may proceed to have the samples Metallographically examined when a metallography microscope is sourced

Multiple tests to firm up the observations were not conducted due to the competing need of using the same sample preparation and testing equipment for production.

III. CHAPTER 3

3.0 RESULTS/CALCULATIONS

3.1 Results

Six quenched mill balls held for various times prior to tempering were designated as 0 Hrs. Before, 0 Hrs. After, 2 Hrs., 4 Hrs., 6 Hrs. and 12 Hrs. The 0 Hrs. Before and 0 Hrs. After samples were standard samples that were not detained prior to tempering at the beginning of the experiment and at the end of the experiment respectively. The 2 Hrs., 4 Hrs., 6 Hrs. and 12 Hrs. samples were detained for two, four, six and twelve hours respectively.

Chemical composition of the investigated samples was obtained from the raw material

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manufacturers' certificates and is as shown in Table 2 below. The carbon content of the samples shows that the steel fell in the eutectoid region of the Iron–Carbon Phase diagram.

Fig. 8: Picture of Prior to Tempering Samples (SOURCE: Author)

Fig. 8 shows forged mill balls that were collected after quenching. The 0 Hr. - Before sample had already been tempered (at 08:15 hrs.) at the time the picture was taken while the 0 Hrs. – After sample was yet to be sampled.

Table 1: Sample Designation of Quenched Balls

Sample Label	**0 Hrs. Before**	**0 Hrs. After**	**2 Hrs.**	**4 Hrs.**	**6 Hrs.**	**12 Hrs.**
Hold Time Prior to Temper	0 Hours At beginning of test	0 Hours At end of test	2 Hours	4 Hours	6 Hours	12 Hours

Table 2: Chemical Composition **(%)** of the samples

C	**Mn**	**Si**	**P**	**S**	**Cr**	**Ni**	**Mo**	**Cu**
0.70-0.90	0.80-1.02	0.20-0.40	<0.022	<0.022	0.70-1.05	≤0.10	0.03-0.15	≤015

*The balance is Fe and trace elements

The chemical composition of the samples was obtained from the certificates of the raw material Manufacturers.

The temperatures of the balls, as they awaited tempering, were recorded. These showed that the rate of temperature drop was rapid within the first 2 hours, dropping down from 66 ^{c}o. to 35^{o}C for the 12-hour sample and thereafter the rate became slower as it approached room temperature. This is as can be seen from Table 3 and Fig. 9 below.

The temperature drop to ambient (31^{o}C) occurred within the first three hours as observed on the sample that was detained for 12 hours prior to tempering (Refer table 3).

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Table 3: Hourly Temperature Readings of the Samples Prior to Tempering

Sample	Hourly Temperatures (ºC)							
	0 Hour	1st Hour	2nd Hour	3rd Hour	4th Hour	5th Hour	6th Hour	7th - 12th Hours
0 Hrs. Before	66	-	-	-	-	-	-	-
0 Hrs. After	66	-	-	-	-	-	-	-
2 Hrs.	66	44	35	-	-	-	-	-
4 Hrs.	66	44	35	32	31	-	-	-
3 Hrs.	66	44	35	33	31	31	31	-
12 Hrs.	66	44.	35	33	31	31	31	30 To 28

Table 3 above shows the hourly temperature readings obtained prior to tempering the sampled balls. The same is represented graphically in figure 9 below.

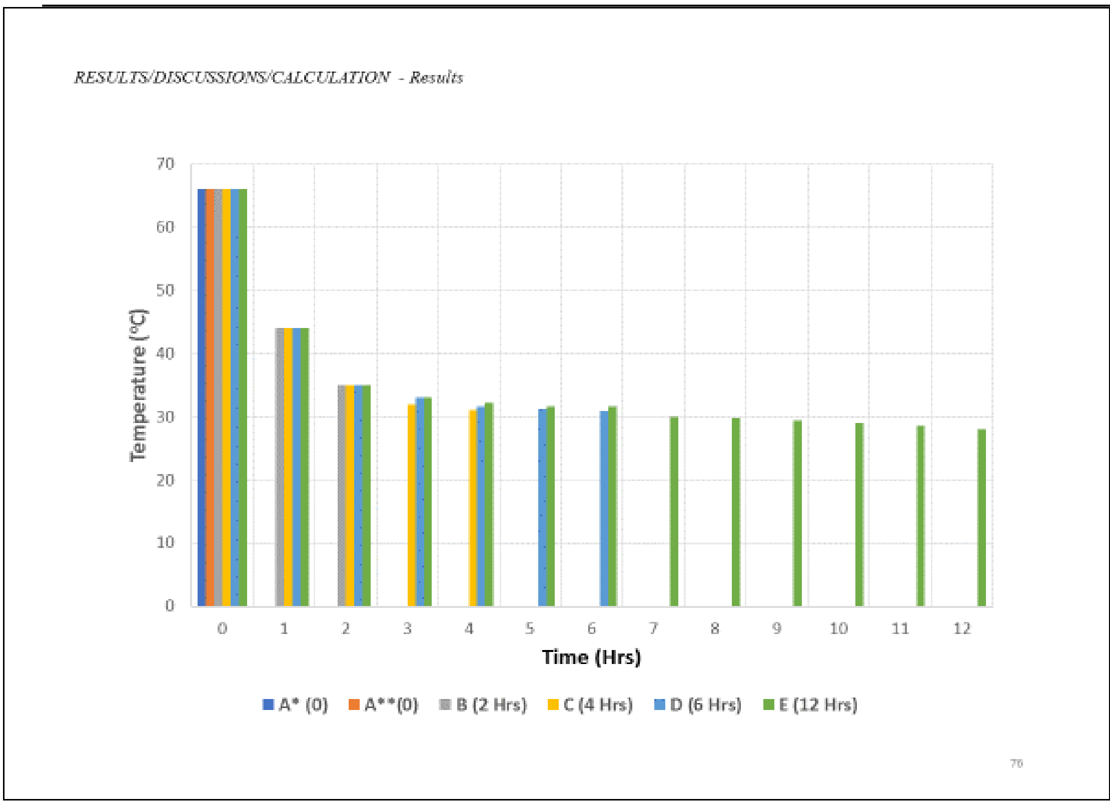

Figure 9: Graph Showing Prior to Tempering Temperatures of the samples

(SOURCE: Author)

Hardness profile tests conducted on all the samples revealed that standard samples that were not detained between quenching and tempering gave the best results in terms of hardness profile as well as the best volumetric hardness. This is as can be seen in in Table 4 and Fig. 10 and Fig.11 below.

The Surface hardness for all the samples was comparable, up to a depth of about 30mm and

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ranged between 58 and 60.5 HRC. This is as can been seen from Table 4 and Fig. 10 below. However, as the profile approached the core, lower hardness values were observed with prolonged time interval between quenching and tempering, except for the sample that was held back for 12 hours. Values obtained for all the samples at >58 HRC, for the surface hardness, > 55 HRC for the core hardness and > 58 HRC for the volumetric hardness were acceptable in as far as the factory production hardness target is concerned i.e. >58 HRC, >53HRC and >55 HRC for the surface hardness, Core hardness and volumetric hardness respectively.

Table 4a: Averaged Hardness Profile values of Ball Samples after Tempering (at depth of 3.0mm to 43.0mm from the surface)

Ball Sample	**Dia. (mm)**	**Wt. (Kg)**	**HRC Hardness at Depth from Surface (mm)**								
			3.0	**8.0**	**13.0**	**18.0**	**23.0**	**28.0**	**33.0**	**38.0**	**43.0**
0 Hrs. Before	140.87	11.40	59.4	59.4	59.2	59.3	59.0	59.3	59.4	58.8	59.4
0 Hrs. After	141.03	11.36	59.5	59.3	59.4	59.9	59.6	59.6	59.0	59.0	59.4
2 Hrs.	141.19	11.42	59.5	59.2	58.9	59.3	59.1	58.8	58.8	57.8	57.9
4 Hrs.	141.14	11.38	60.5	60.1	60.0	59.0	59.4	59.5	57.6	58.5	57.2
6 Hrs.	141.30	11.42	59.4	58.6	58.6	59.0	59.1	58.7	58.8	57.8	57.9
12 Hrs.	140.36	11.36	59.5	58.3	59.2	59.1	59.0	59.5	58.9	58.7	58.7

Table 4b: Averaged Hardness Profile values of Ball Samples after Tempering (at depth of 48.0mm to 73.0mm from the surface)

Ball Sample	**Dia. (mm)**	**Wt. (Kg)**	**HRC Hardness at Distance from Surface (mm)**						
			48.0	**53.0**	**58.0**	**63.0**	**68.0**	**73.0**	Volumetric Hardness
0 Hrs. Before	140.87	11.40	58.6	58.9	58.2	57.7	58.5	57.9	59.1
0 Hrs. After	141.03	11.36	59.4	59.2	58.6	58.9	58.7	58.4	59.0
2 Hrs.	141.19	11.42	57.9	58.2	58.4	56.9	57	56.7	59.0

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4 Hrs.	141.14	11.38	57.2	57.2	58.7	57.2	58.5	56.8	58.9
6 Hrs.	141.30	11.42	57.9	57.6	56.3	56.9	56.6	55.2	59.1
12 Hrs.	140.36	11.36	58.7	58.6	58.8	59.2	59.5	58.9	59.1

Table 4 above shows averaged HRC hardness values taken at various depths from the ball surface

Table 5a: Detailed Hardness Profile values of Ball Samples after Tempering (at depth of 3.0mm to 43.0mm from the surface)

SAMPLE	**Dia. (mm)**	**Wt. (Kg)**	**Test Point**	**HRC Hardness at Distance from Surface (mm)**								
				3.0	**8.0**	**13.0**	**18.0**	**23.0**	**28.0**	**33.0**	**38.0**	**43.0**
0 Hrs. Before	140.87	11.40	1	59.3	59.3	59.1	59.1	59.1	59.4	59.3	58.4	59.3
			2	59.4	59.4	59.2	59.3	59.0	59.3	59.4	58.8	59.4
			3	59.6	59.6	59.3	59.5	58.9	59.2	59.5	59.1	59.6
			Average	**59.4**	**59.4**	**59.2**	**59.3**	**59**	**59.3**	**59.4**	**58.8**	**59.4**
0 Hrs. After	141.03	11.36	1	59.5	59.1	59.1	59.3	59.7	59.5	58.5	58.8	58.6
			2	59.6	59.5	59.4	59.3	59.4	59.7	59.4	59.3	59.7
			3	59.5	59.4	59.7	61.0	59.7	59.5	59.2	58.9	59.8
			Average	**59.5**	**59.3**	**59.4**	**59.9**	**59.6**	**59.6**	**59.0**	**59.0**	**59.4**
2 Hrs.	141.19	11.42	1	59.6	59.1	58.5	59.2	58.7	58.5	59.0	56.5	58.3
			2	59.6	59.6	59.5	59.4	59.5	58.8	59.0	58.4	57.0
			3	59.4	58.9	58.7	59.2	59.1	59.0	58.5	58.5	58.4
			Average	**59.5**	**59.2**	**58.9**	**59.3**	**59.1**	**58.8**	**58.8**	**57.8**	**57.9**
4 Hrs.	141.14	11.38	1	60.4	60.1	60.1	58.7	59.5	59.5	57.6	58.3	57.4
			2	60.5	59.8	60.3	59.0	59.4	59.4	57.4	58.3	56.8
			3	60.7	60.3	59.7	59.3	59.3	59.6	57.9	58.9	57.5
			Average	**60.5**	**60.1**	**60.0**	**59.0**	**59.4**	**59.5**	**57.6**	**58.5**	**57.2**
6 Hrs.	141.30	11.42	1	59.6	58.5	59.0	59.0	59.4	58.3	58.8	57.9	57.9
			2	59.6	58.7	58.1	58.8	58.6	58.7	59.0	57.9	58.1
			3	58.9	58.6	58.7	59.3	59.2	59.0	58.6	57.7	57.7
			Average	**59.4**	**58.6**	**58.6**	**59**	**59.1**	**58.7**	**58.8**	**57.8**	**57.9**
12 Hrs.	140.36	11.36	1	59.4	58.3	59.1	59.1	59.0	60.0	59.2	58.1	59.2
			2	59.2	59.2	58.7	58.8	59.1	59.2	58.9	58.8	58.2
			3	59.8	57.4	59.7	59.5	58.8	59.2	58.6	59.2	58.6
			Average	**59.5**	**58.3**	**59.2**	**59.1**	**59.0**	**59.5**	**58.9**	**58.7**	**58.7**

Table 5b: Detailed Hardness Profile values of Ball Samples after Tempering (at depth of 48.0mm to 73.0mm from the surface)

BALL SAMPLE	Dia. (mm)	Wt. (Kg)	Test Point	HRC Hardness at Distance from Surface (mm)						
				48.0	53.0	58.0	63.0	68.0	73.0	Volumetric Hardness
0 Hrs. Before	140.87	11.40	1	58.7	59.1	58.4	57.5	58.6	59.0	
			2	58.5	58.9	58.2	57.7	58.5	56.0	
			3	58.5	58.8	57.9	57.8	58.3	58.8	
			Average	**58.6**	**58.9**	**58.2**	**57.7**	**58.5**	**57.9**	59.3
0 Hrs. After	141.03	11.36	1	58.8	58.7	58.5	58.7	57.9	57.3	
			2	59.3	58.5	59.3	58.4	58.4	58.1	
			3	59.5	58.7	58.8	59.0	58.8	59.2	
			Average	**59.4**	**59.2**	**58.6**	**58.9**	**58.7**	**58.4**	59.6
2 Hrs.	141.19	11.42	1	58.1	58.1	56.0	57.3	58.0	56.8	
			2	57.8	59.1	56.1	56.0	56.5	56.2	
			3	58.7	57.9	58.6	57.7	55.7	54.1	
			Average	**57.9**	**58.2**	**58.4**	**56.9**	**57.0**	**56.7**	59.0
4 Hrs.	141.14	11.38	1	57.7	58.7	56.5	57.5	57.1	59.2	
			2	56.9	59.0	58.3	58.9	57.4	59.2	
			3	56.6	58.4	56.7	59.0	56.0	57.3	
			Average	**57.2**	**57.2**	**58.7**	**57.2**	**58.5**	**56.8**	59.1
6 Hrs.	141.30	11.42	1	56.8	57.4	56.2	56.2	54.6	53.1	
			2	59.0	56.3	58.4	57.5	55.7	56.4	
			3	57.1	55.3	56.1	56.0	55.2	58.1	
			Average	**57.9**	**57.6**	**56.3**	**56.9**	**56.6**	**55.2**	58.9
12 Hrs.	140.36	11.36	1	58.7	59.2	59.2	59.2	59.4	57.6	
			2	58.8	58.1	58.9	59.7	58.5	58.2	
			3	58.2	59.1	59.6	59.5	58.8	57.0	
			Average	**58.7**	**58.6**	**58.8**	**59.2**	**59.5**	**58.9**	59.1

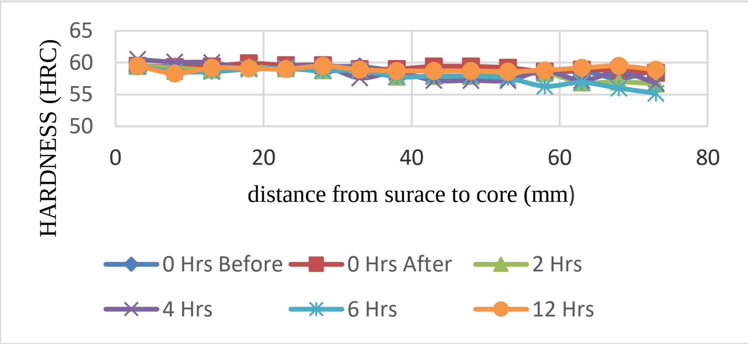

Figure 10: Graph Showing the hardness profile (SOURCE: Author). *Figure 10 shows the hardness profile obtained from 0Hrs (Before and After), 2Hrs, 4 Hrs., 6Hrs and 12 Hrs. holding time before quenching.*

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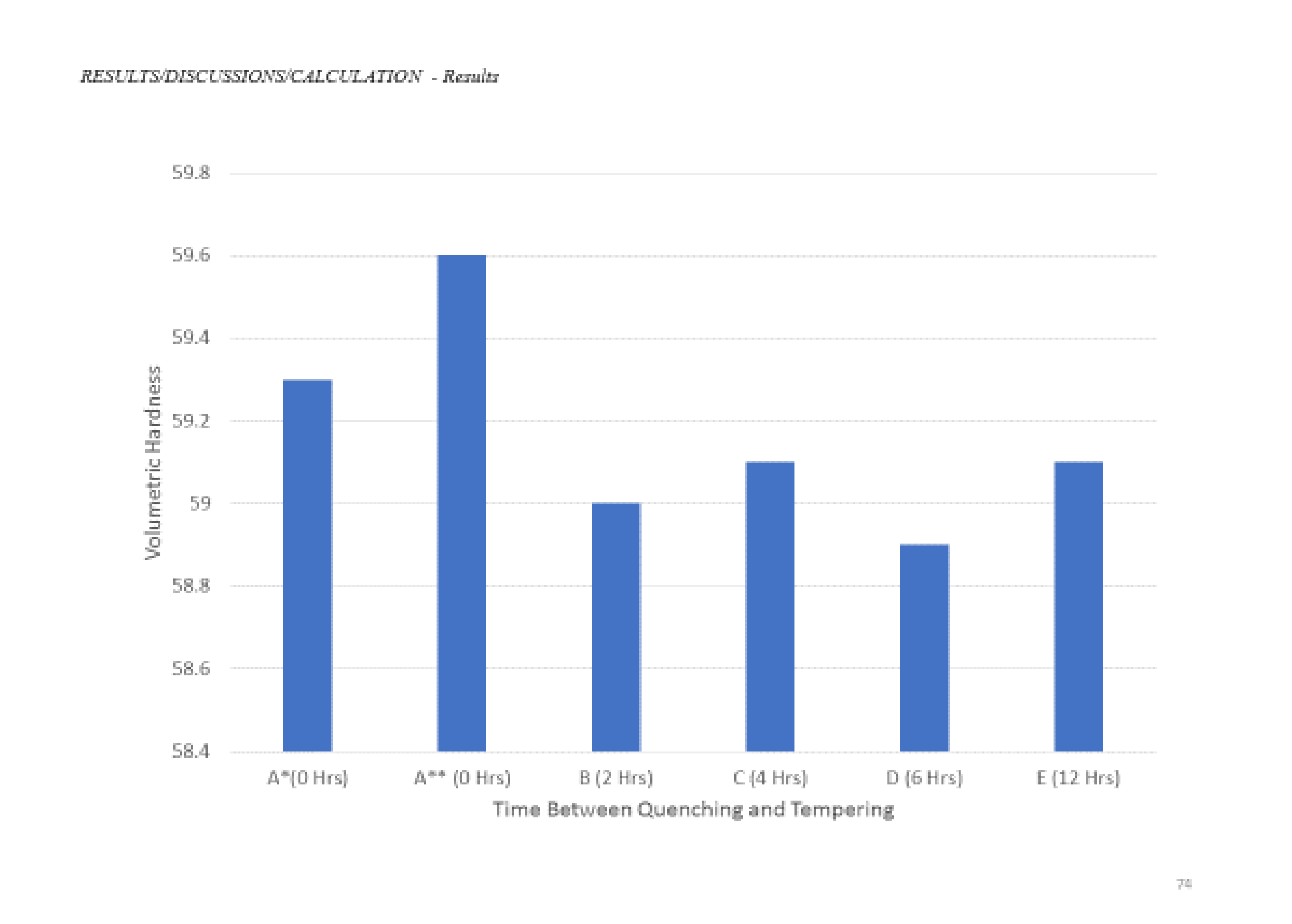

Figure 11: Graph Showing Volumetric Hardness of the samples (SOURCE: Author)

Figure 11 shows the Volumetric hardness obtained from 0Hrs (Before and After), 2Hrs (B), 4 Hrs. (C), 6Hrs (D) and 12 Hrs. (E) holding time before quenching

All the ball samples were split open and had their internal examined visually. Visual examination showed that there was No significant difference in the grain structures of the delayed tempered balls when compared with that of the balls that followed the normal process.

The internal structures of all the balls also revealed No cracks or flaws as shown in figures 12a, 12b and 12c below. Literature reviewed indicated that various types of steel respond differently when tempering is delayed after quenching. Some steels are quite sensitive to quench cracking while others are less sensitive. Since no flaws were observed in the internal structure, this type of steel could be one of those that are less sensitive to cracking after quenching.

Fig. 12a: Internal of Split Balls (0 Hrs. – Before and 0 Hrs. - After) (SOURCE: Author)

Fig. 12a - Visual inspection of the internal structures of standard samples that were not detained (0 Hrs.) prior to tempering showing no internal flaws.

Figure 12b: Internal of Split Balls (2Hrs and 4 Hrs.) (SOURCE: Author)

Fig. 12b -Visual inspection of the internal structures of samples that were detained for 2 and 4 Hours prior to tempering, showing no internal flaws.

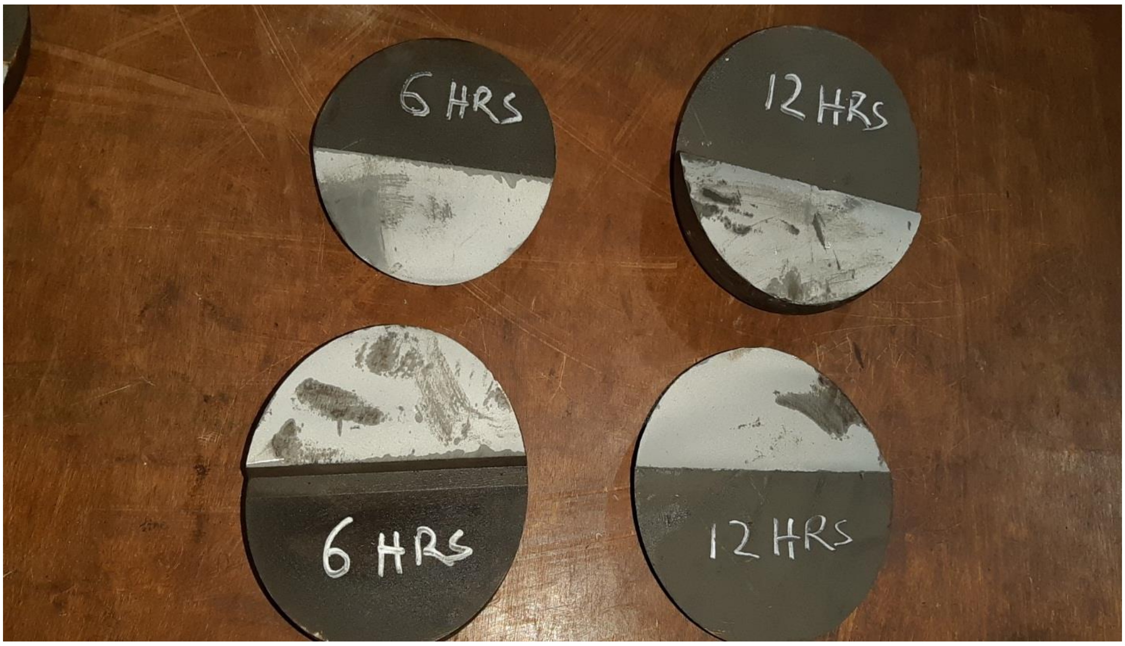

Fig. 12c: Internal of Split Balls (6 Hrs. and 12 Hrs.) (SOURCE: Author)

Fig. 12c - Visual inspection of the internal structures of samples that were detained for 6 and 12 Hours prior to tempering, showing no internal flaws.

Non-Destructive Testing (Penetrant Testing) conducted on the samples revealed no flaw indications on all the samples. The samples were first thoroughly cleaned with the help of a penetrant remover, which is a solvent. After drying the samples were sprayed with penetrant and allowed to dwell for 15 minutes before being wiped out thoroughly with the help of the penetrant remover and a clean cloth. The developer was then sprayed on the samples which were then inspected to see if there was any penetrant sipping out of the samples which would indicate flaws.

Fig. 13: Cut and Polished Sample undergoing NDT- Liquid Penetrant Tests (SOURCE: Author)

Fig. 13 showing Cut Samples sprayed with Liquid Penetrant during an NDT Test

Fig. 14: NDT Developer Sprayed Samples (SOURCE: Author)

Fig. 14 showing Picture of Developer sprayed samples in a Liquid Penetrant NDT test showing no flaws

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Metallography examination had not yet been conducted at the time of reporting. A metallography microscope was yet to be sourced.

It was initially planned to conduct Drop Ball Tests on a different set of samples with similar investigated parameters, but this was not done due to the competing need of first attending to production samples. However, based on some previous drop ball test that was conducted while investigating the effect of Re-Tempering similar type of balls, it was supposed that these balls could pass the test.

3.2 Calculations

Volumetric Hardness Calculations:

Volumetric Hardness = (0.289*TS) + (0.436*0.25T) + (0.203*0.5T) + (0.063*0.75T) + (0.009*TC)

Where TS = Surface Hardness

0.25T= Hardness at 0.25 of ball radius depth

0.5T = Hardness at 0.5 of ball radius depth

0.75T= Hardness at 0.75 of ball radius depth

TC = Hardness at centre of grinding

(SOURCE: energosteel.com)

IV. CHAPTER FOUR

4.0 Conclusion and Recommendations

4.1 Conclusion

The Effect of prolonged time interval between quenching and tempering on the hardness profile of the 140mm forged steel mill balls manufactured at MELongteng was as follows:

There was no significant effect on the surface hardness up to a depth of about 30mm from the surface towards the core. Lower hardness values were however observed with prolonged time intervals between quenching and tempering as the profile approached the core, except for the sample that was held back for 12 hours.

The volumetric hardness values obtained with samples that were not detained between quenching and tempering were better than those obtained from samples that were detained.

Samples that were not detained between quenching and tempering gave the best hardness profile as well as the best volumetric hardness values. However, values obtained for all the samples (i.e. including those that were detained between quenching and tempering) in terms of surface hardness, core hardness and volumetric hardness were acceptable in as far as the factory production hardness targets were concerned.

Visual examination as well as Non-Destructive Testing of the internal structures of all the samples revealed no flaws. There was also no significant difference, visually, in the grain structures of the delayed tempered balls when compared with those that followed the normal process.

With the foregoing, it can be concluded that prolonged time interval between quenching and tempering caused by power outage had a slight negative effect on the hardness profile of the 140mm forged steel mill balls manufactured at MELTZ. The deterioration experienced, however, still left the product to be within the targeted acceptable quality limits and could be used in industry with negligible negative effect.

4.2 Recommendations

It is recommended that

- Multiple tests should be conducted in order to firm up the findings observed in this project.

- Drop ball tests should be done on the products of prolonged time interval samples in order to conclusively determine whether such mill balls can perform as expected when used in industry.

- Metallography examination be conducted on the investigated samples to ascertain the microstructures obtained from the different detention time intervals.

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