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EFFECT OF HOT FORGING ON CHEMICAL COMPOSITION AND METALLOGRAPHIC STRUCTURE OF STEEL ALLOYS

Effect of Hot Forging on Chemical Composition and Metallographic Structure of Steel Alloys

[Case Study on Din-100CrMn6 Steel]

Shishay Amare Gebremeskel[α] & Prof. Ratnam Uppala (Ph.D)[σ]

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With small amounts of cementite at grain boundaries are observed at raw material stage. On the second test stage, the amount of C, Si, Mn, and Cr slightly decreased. This is due to decarburization and oxidation, upon heating to the forging temperature. Still the composition of the alloy steel is in accepted limits. At third stage while heat treatment of forged balls serious deviation occurred in the process, severe decarburisation and oxidation occurred and the chemical composition of alloy heat-treated balls changed to unacceptable levels reslting total rejection of total product. Based on these observed test results, the material used, and the process environment, solutions for the existing problem were addressed. Customization of the existing forging process and fixing of the temperature controllers for the furnaces in addition to careful selection of heat treatment mediums are important. Following the standard temperature sets for each type of heat treatment and applying appropriate soaking time to the corresponding material is highly recommended.

Keywords : Hot forging, chemical composition, metallographic structure, defects, DIN-100CrMn6, oxidation and decarburization.

I. Introduction

Forging is the working of metal in to a useful shape by hammering or pressing. It is the oldest of the metal working arts, having its origin with the primitive black smith of Biblical time. The development of machinery to replace the arm of the smith occurred early during the industrial revolution. Today there is a wide variety of forging machinery which is capable of making parts ranging in size from a bolt to a turbine rotor or an entire airplane wing. Most forging operations are carried out hot, although certain metals may be cold- forged. Two major classes of equipment are used for forging operations. The forging hammer, or drop hammer, delivers rapid impact blows to the surface of the metal, while the forging press subjects the metal to a slow- speed compressive force [1]. Since heating the preformed billet up to the forging temperature is a must in hot forging, the temperature in combination with the further process of forging alters the metallographic structure and the material composition of the parent material.

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II. Classifications of Forging Process

a) Open die forging (ODF)

In its simplest form, open die forging generally involves placing a solid cylindrical work piece between two flat dies (platens) and reducing its height by compressing it. This operation is also known as upsetting. The die surface may be shaped, as conical or curved cavity, there by forming the ends of the cylindrical work piece during upsetting [2]. Since more surface of the billet is exposed to atmosphere it attains high convection heat loss and it oxidizes contents of the material and creates scales on the surface and intermolecular boundaries.

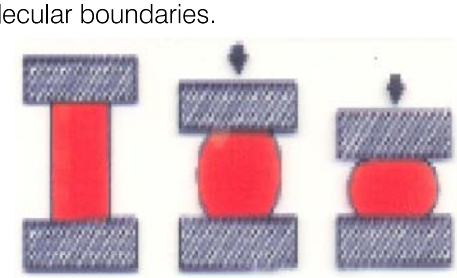

Fig. 1 : Upsetting of a cylinder, in open die forging.

b) Closed die forging (CDF)

In true closed die forging no flash is formed and the work is completely surrounded by the die. In impression die forging any excess metal in the die cavity is formed in to a flash, but this is not the case in closed die forging. Thus proper control of the volume of the material is essential to obtain a forging of desired dimensions. Under sized blanks in closed die forging prevent the complete filling of the die; over sized blanks may cause premature die failure or jamming of the dies [2]. In this type of forging the billet has very short time to be exposed to atmosphere and hence less oxidation. The main effect here is from the conduction heat transfer through the dies and intermolecular reaction of the material contents that results scales between intermolecular boundaries.

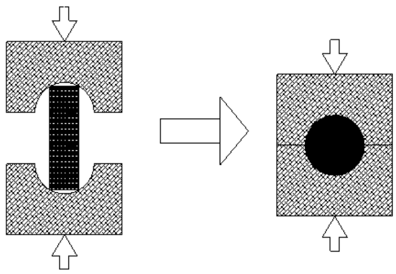

Fig. 2 : Illustration of perfect closed die forging (with no flash)

c) Impression die forging (IDF)

In impression die forging, the work piece acquires the shape of the die cavities (impressions) while it is being upset between the closing dies. Some of the material flows radially out ward and forms a flash. Because of its high length- to- thickness ratio, the flash is subjected to high pressure. These pressures in turn mean high frictional resistance to material flow in the radial direction with in the flash gap. Because high friction encourages the filling of the die cavities, the flash has a significant role in the flow of material in impression die forging.

Furthermore, if the operation is made at elevated temperatures, the flash, because of its high surface to thickness ratio, cools faster than the bulk does and helps fill the die cavities [2].

In this process material is affected by convection heat loss and surface oxidation through and on the flash. Conduction heat transfer through on work piece-dies interface and intermolecular reaction of the material contents have similar effects as in closed die forging.

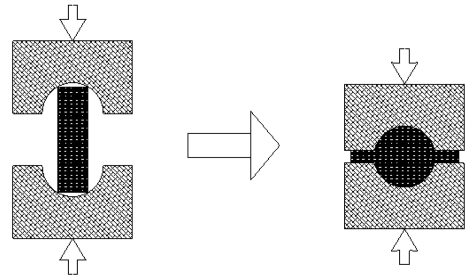

Fig. 3 : Illustration of impression die forging (with flash)

From the above classification of forging process forging of mill grinding steel balls, an interest of this research, lie on impression die forging.

The hot forged mill grinding steel balls produced has got defects like surface and internal scales, cracks, and loss of expected hardness and strength. So it is mandatory to study the effect of heating the bulk, forging environment, and the further progress of the forging process from the start up to the end.

III. Motivation

Development in forging process industries show the range of advancement from a simple upsetting of open die forging to the high precision closed die forging. Hot closed die forgings or hot impression die forgings are the most widely applicable forging processes for products having intricate shape and demanding high precision. Dies with different shapes of cavities corresponding to the product required are mounted on a forging machine and necessary type of loading on a heated billet via the dies is applied to deform the work piece in to required shape, hence hot closed/impression die forging. While doing this, the result of the deformation will depend on the type and inclusions of material, the cavity geometry, the amount of load, the type of loading, the material temperature, the die-work piece interface condition, and other variables.

A b c

Fig. 4 : a) steel balls b) steel ball forging dies c) trimming dies; photo from Akaki Basic Metals Industry

The specific product, forged mill grinding steel ball of cement delivered from **Akaki Basic Metals Industry,** my target industry, is produced using hot impression die forging process. Steel material, with DIN standard of 100CrMn6, is used and cement balls were produced and supplied to their customer, **Mugher Cement Industry**. **Mugher Cement Industry** has got these balls as 100% defective after a 15 days service life. Due to this reason the industry has already stopped producing steel balls for cement industries and exposed to huge losses.

This is the main motivation to carry on this research, focusing on the material evaluation of the product with respect to its material content and metallographic structure. Thus, these tests are done and compared with the parent material condition. This will help the factory to think over the solutions adjust the forging process parameters and behaviour of the forging environment.

IV. Materials and Methods

Here literatures starting from about three decades ago are reviewed with a main focus on studying the effect of forging process on the material properties. For this purpose laboratory tests are conducted as a method for the research. At the same time, background of the research is also included.

a) Basics of Forging Process

In forging an initially simple part (a billet), for example, is plastically deformed between two tools (or dies) to obtain the desired final configuration. Thus, simple part geometry is transformed into a complex one, whereby the tools "store" the desired geometry and impart pressure on the deforming material through the tool/material interface. Forging processes usually produce little or no scrap and generate the final part geometry in a very short time, usually in one or a few strokes of a press or hammer. As a result, forging offers potential savings in energy and material, especially in medium and large production quantities, where tool costs can be easily amortized. In addition, for a given weight, parts produced by forging exhibit better mechanical and metallurgical properties and reliability than do those manufactured by casting or machining.

Forging is an experience-oriented technology. Throughout the years, a great deal of know-how and experience has been accumulated in this field, largely by trial-and-error methods. Nevertheless, the forging industry has been capable of supplying products that are sophisticated and manufactured to very rigid standards from newly developed, difficult-to-form alloys. The physical phenomena describing a forging operation are difficult to express with quantitative relationships. The metal flow, the friction at the tool/material interface, the heat generation and transfer during plastic flow, and the relationships between microstructure/properties and process conditions are difficult to predict and analyze. Often in producing discrete parts, several forging operations (pre-forming) are required to transform the initial "simple" geometry into a "complex" geometry, without causing material failure or degrading material properties.

Consequently, the most significant objective of any method of analysis is to assist the forging engineer in the design of forging and/or performing sequences. For a given operation (pre-forming or finish forging), such design essentially consists of (a) establishing the kinematic relationships (shape, velocities, strain rates, strains) between the deformed and un-deformed part, i.e., predicting metal flow, (b) establishing the limits of formability, i.e., determining whether it is possible to form the part without surface or internal failure, and (c) predicting the forces and stresses necessary to execute the forging operation so that tooling and equipment can be designed or selected, Shirgaokar [27].

Relating to the compressive nature of forging process, Ettouney and Hardt (1983) [4] aimed to predict failure of specimens undergoing compression so as to permit maximum deformation before unloading and stress relieving. In this paper a method for determining flow stress characteristics of a cylindrical compression specimen is introduced, so that the state of stress at the surface can be found. They determined flow stress using measurements that can be made in- process, i.e., compression force, height reduction, and bulge radius.

Grobaski (2004) [13] noted about hot forging that it is a forging process done where the work piece is heated up to about 75% of its melting temperature. As the temperature of the work piece, prior to forging approaches the melting temperature, the flow stress and energy required to form the material is decreased. Therefore, the strain rate or rate of production can be increased.

Tremaine (2005) [18] characterized the defects of four different sample materials using a light microscope and summarized that hydrogen flake and voids are the main internal defects.

Durakan [11] stated the industrial applications and advantages of the induction heating in hot forging and the induction heating furnace units and the operating parameters affect the resultant temperature of the heated billet. The operating parameters are like power supplied, conveyor speed, and the induction coil box, hole, diameter. Michael L.He (2007) [17] put the metallographic photos for different defects and interpreted them by grouping as raw material, forge, heat treat, and unusual defect types.

b) Hot Impression Die Forging

The forging and its variety hot closed-die-forging (CDF), (or hot impression forging), beyond any doubt, is the oldest metal processing technology. It started when the prehistoric people learned to smith virgin gold peaces and later to heat sponge iron and to beat it with a stone in order to form useful implements.

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For a long time forging has strongly depended upon, first and foremost, skills of the blacksmith and from that point of view it related to the arts. In opposite to its practice, the theoretical grounds, which roots are deep in to two fundamental sciences – the continuum mechanics and metal physics – are relatively young and have been developing very intensively [21].

Hot impression die forging is the plastic deformation of metal between die halves which carry the impressions of the desired final shape, at a temperature and strain rate such that re-crystallization occurs simultaneously with deformation, thus avoiding strain hardening. For this to occur, high work piece temperature (matching the metal's re-crystallization temperature) must be attained throughout the process, so energy needed for this preheating. By hot forging, it can be produced a great variety of shapes with virtually any steel. The extensive scale formation occurs on the surface of the work piece. Larger tolerances and allowances are needed for further machining. A form of hot forging is isothermal forging, where materials and dies are heated to the same temperature. In nearly all cases, isothermal forging is conducted on super alloys in a vacuum or highly controlled atmosphere to prevent oxidation [10].

c) Hot Impression Die Forging as a System

Hot impression die forging system, as in other forging systems, comprises all the input variables such as the billet or blank (geometry and material), the tooling (geometry and material), the conditions at the tool/material interface, the mechanics of plastic deformation, the equipment used, the characteristics of the final product, and finally the plant environment where the process is being conducted.

The "systems approach" in forging allows study of the input/output relationships and the effect of the process variables on product quality and process economics. Fig.5 below shows the different components of the forging system. The key to a successful forging operation, i.e., to obtaining the desired shape and properties, is the understanding and control of the metal flow. The direction of metal flow, the magnitude of deformation, and the temperatures involved greatly influence the properties of the formed components. Metal flow determines both the mechanical properties related to local deformation and the formation of defects such as cracks and folds at or below the surface [27].

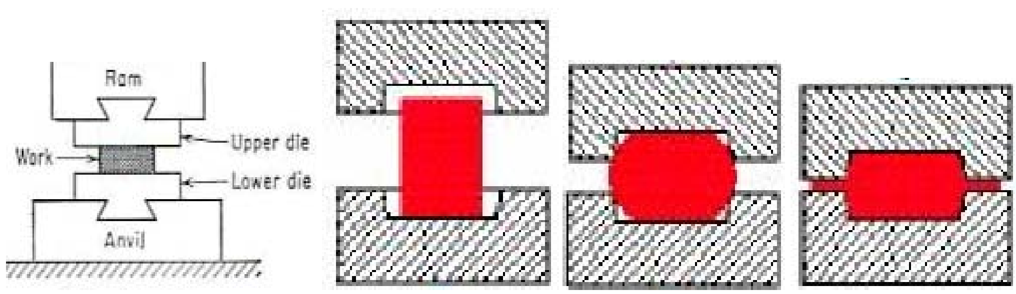

Fig. 5 : Components and progress of a particular hot impression die forging system[27]

i. *Material Characterization*

For a given material composition and deformation/ heat treatment history (microstructure), the flow stress and the workability (or forge-ability) in various directions (anisotropy) are the most important material variables in the analysis of a metal forging process. For a given microstructure, the flow stress, $\bar{\sigma}$, is expressed as a function of strain, $\bar{\varepsilon}$, strain rate, $\dot{\bar{\varepsilon}}$, and temperature, T:

$$\bar{\sigma} = f(\bar{\varepsilon}, \dot{\bar{\varepsilon}}, \mathrm{T}) \qquad (2.1)$$

To formulate the constitutive equation (Eq.2.1), it is necessary to conduct torsion, plane-strain compression, and uniform axi-symmetric compression tests. During any of these tests, plastic work creates a certain increase in temperature, which must be considered in evaluating and using the test results. Workability, forge-ability, or formability is the capability of the material to deform without failure; it depends on (a) conditions existing during deformation processing (such as temperature, rate of deformation, stresses, and strain history) and (b) material variables (such as composition, voids, inclusions, and initial microstructure). In hot forging processes temperature gradients in the deforming material, due to local die chilling for example, also influence metal flow and failure phenomena [27].

ii. *Tooling and Equipments*

The selection of a machine for a given process is influenced by the time, accuracy, and load/ energy characteristics of that machine. Optimal equipment selection requires consideration of the entire forging system, including lot size, conditions at the plant, environmental effects, and maintenance requirements, as well as the requirements of the specific part and process under consideration. The tooling variables include (a) design and geometry, (b) surface finish, (c) stiffness, and (d) mechanical and thermal properties under conditions of use.

iii. *Friction and Lubrication at the Die-Work Piece Interface*

The mechanics of interface friction are very complex. One way of expressing friction quantitatively is through a friction coefficient, μ, or a friction shear factor, m. Thus, the frictional shear stress, τ, is:

$$\boldsymbol{\tau} = \mu\sigma_n \quad (2.2)$$

Or

$$\boldsymbol{\tau} = f\,\bar{\sigma} = \frac{m}{\sqrt{3}}\bar{\sigma} \quad (2.3)$$

Where σ_n is the normal stress at the interface, $\bar{\sigma}$ is the flow stress of the deforming material and f is the friction factor ($f = \frac{m}{\sqrt{3}}$). There are various methods of evaluating friction, i.e., estimating the value of μ or m. In forging, the most commonly used tests are the ring compression test, spike test, and cold extrusion test [27].

iv. *Deformation Zone and Mechanics of Deformation*

In forging, material is deformed plastically to generate the shape of the desired product. Metal flow is influence mainly by (a) tool geometry, (b) friction conditions, (c) characteristics of the stock material, and (d) thermal conditions existing in the deformation zone. The details of metal flow influence the quality and properties of the formed product as well as the force and energy requirements of the process. The mechanics of deformation, i.e., the metal flow, strains, strain rates, and stresses, can be investigated by using one of the approximate methods of analysis (e.g., finite-element analysis, finite difference, slab, upper bound, etc.).

v. *Properties and Geometry of the Product*

The macro- and micro-geometry of the product, i.e., its dimensions and surface finish, are influenced by the process variables. The processing conditions (temperature, strain, strain rate) determine the micro-structural variations taking place during deformation and often influence the final product properties. Consequently, a realistic systems approach must include consideration of (a) the relationships between properties and microstructure of the formed material and (b) the quantitative influences of process conditions and heat treatment schedules on micro-structural variations.

d) Possible Defects of Hot Impression Die Forging Products of Alloy Steels

Dieter (1988) [1] discussed that the common defects in forging are, surface cracking, cracking at the flash, cold shut (fold), and internal cracking. Surface cracking can occur as a result of excessive working of the surface at too low a temperature or as a result of hot shortness (high sulphur content). Cracking at the flash of closed die (impression die) forgings is another surface defect since the crack generally penetrates in to the body of the forging when the flash is trimmed off. This can be avoided by increasing the flash thickness, relocating the flash to a less critical region, hot trimming, or stress relieving the forging prior to cold trimming of the flash. Another common surface defect of impression die forging is the cold shut or fold. It is produced when two surfaces of metal fold against each other without welding completely. This can happen when metal flows past part of the die cavity that has already been filled or that is only partly filled because the metal failed to fill in due to a sharp corner, excessive chilling, or high friction. A common cause of cold shuts is too small die radius.

Loose scale or lubricant residue that accumulates in deep recesses of the die forms scale pockets and causes under fill. Incomplete de-scaling of the work piece results in forged-in scale on the finished part.

Secondary tensile stresses can develop internal cracks, especially during upsetting of a cylinder or a round, as a result of the circumferential tensile stresses. It can be minimized by proper die design, using concave dies. Internal cracking is less prevalent in impression die forging because compressive stresses are developed by the reaction of the work with the die wall. Small crack, or flakes at the centre of the cross section can be occurred after cooling due to the development of residual stresses, especially in large forgings, associated with high hydrogen content.

As far as the reviewed studies of former research journals and books above, there is no as such clear study, particularly, focusing on the forged mill grinding steel ball of cement. This paper mainly emphasized on testing the material, studying the test results to help to interpret them, and to suggest the root causes for the defective balls, and suggesting the possible solutions.

e) Material Evaluation by Laboratory Tests

Metallographic and Spectrometry Tests

An experiment of metallographic structure and spectrometry (material composition) is done at three stages of the particular forging process of 100CrMn6 steel ball. Stage-1: Testing the raw material; Stage-2: testing just as forged; and Stage-3: testing the heat treated final product; is conducted following the standard procedures.

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Fig. 6 : Photos while the author conducting the experiment.

Stage-1: Testing the raw material

The chemical composition and the metallographic structure of the *raw material (billet)* for the particular product, mill grinding steel ball of DIN 100CrMn6, are tested and observed. The test results are as follows:

Table 1 : Observed chemical composition of the tested raw material

Steel designation	Percentage composition of elements in the 100CrMn6 steel alloy (%)									
	C	Si	Mn	Cr	P	S	Total	Fe-balance	C+Si+Mn+Cr (important elements)	P+S (detriments)
100CrMn6 observed (raw material)	0.93	0.57	1.18	1.69	0.03	0.022	4.422	95.578	4.37	0.052

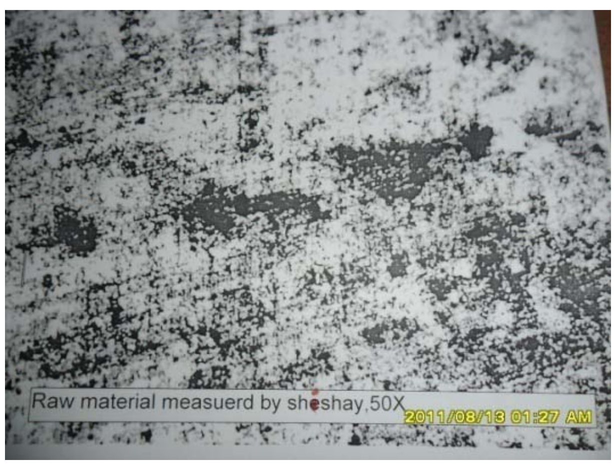

Fig.7 : Observed metallographic structure of the tested raw material (50X)

Stage-2: Testing just as forged

The chemical composition and the metallographic structure of the *as forged product*, mill grinding steel ball of DIN 100CrMn6, are tested and observed. The test results are as follows:

Table 2 : Observed chemical composition of the as forged product

Steel designation	Percentage composition of elements in the 100CrMn6 steel alloy (%)									
	C	Si	Mn	Cr	P	S	Total	Fe-balance	C+Si+Mn+Cr (important elements)	P+S (detriments)
100CrMn6 observed (as forged)	0.92	0.56	1.16	1.63	0.028	0.028	4.326	95.674	4.27	0.056

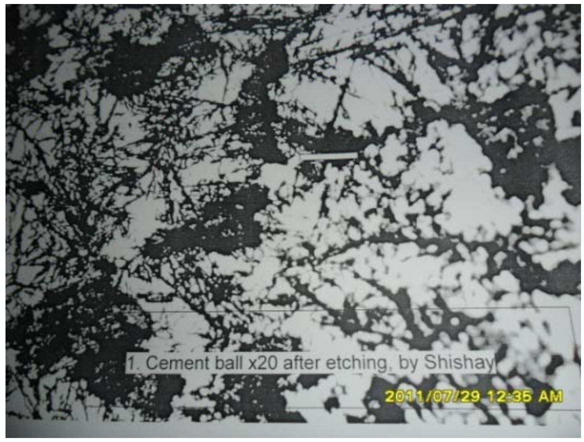

Fig. 8 : Observed metallographic structure of the as forged product (20X)

Stage-3: Testing the heat treated final product

The chemical composition and the metallographic structure of the *heat treated final product*, mill grinding steel ball of DIN 100CrMn6, are tested and observed. The test results are as follows:

Table 3 : Observed chemical composition of the heat treated final product.

Steel designation	Percentage composition of elements in the 100CrMn6 steel alloy (%)									
	C	Si	Mn	Cr	P	S	Total	Fe-balance	C+Si+Mn+Cr (important elements)	P+S (detriments)
100CrMn6 observed (heat treated final product)	0.67	0.339	0.89	0.87	0.039	0.034	2.842	97.158	2.769	0.073

Fig. 9 : Observed metallographic structure of the heat treated final product (20X)

V. Results and Discussions

a) Comparison of Test Results with Existing DIN Standard

Collecting the test results of the above three stages and bringing to one pool will help for ease of comparison and evaluation.

Table 4 : Comparison of observed chemical composition of, the raw material, the as forged, and the heat treated final product, steel ball material with the standard one.

Steel designation	Percentage composition of elements in the 100CrMn6 steel alloy (%)									
	C	Si	Mn	Cr	P	S	Total	Fe-balance	C+Si+Mn+Cr (important elements)	P+S (detriments)
1.3520 steel (100CrMn6) DIN standard	0.95-1.05	0.40-0.65	0.90-1.20	1.30-1.60	0.027	0.02	-------	---------	--------------	-------------
1.3520 steel (100CrMn6) DIN standard (*average*)	1.00	0.525	1.05	1.45	0.027	0.02	4.072	95.928	4.025	0.047
100CrMn6 observed (raw material)	0.93	0.57	1.18	1.69	0.03	0.022	4.422	95.578	4.37	0.052
100CrMn6 observed (as forged)	0.92	0.56	1.16	1.63	0.028	0.028	4.326	95.674	4.27	0.056
100CrMn6 observed (heat treated final product)	0.67	0.339	0.89	0.87	0.039	0.034	2.842	97.158	2.769	0.073

(a) (b) (c)

Fig. 10 : Observation of metallographic structure of, (a) the raw material (50X); (b) the as forged (20X); (c) heat treated final product (20X), 100CrMn6 mill grinding steel ball of cement industries, done in Akaki Basic Metals Industry.

From the chemical composition (Table 4) and metallographic structure (Fig. 10) shown above, the ferrite-pearlite matrix of the raw material (Fig. 10a) with graphite flakes and impurities are concentrated in between the grain boundaries. This ferrite-pearlite matrix has got austenatized and the amount of C, Si, Mn, and Cr decreased due to decarburization and oxidation, upon heating to the forging temperature. The carbides, oxides, and flakes are concentrated more in the boundaries (Fig. 10b) of the austenite grains.

These concentrations cause the propagation of continuous crack during the hardening treatment while the austenite grains are dominantly transformed to bainite (ferrite + cementite) (Fig. 10c).

Expressing the fall of the chemical composition of the important alloying elements and rise of the detrimental ones with respect to the Fe-balance, graphically, is very important and is shown bellow. The trend of fall and rise of the elements is done along test stages starting from the DIN standard value up to the third test stage. Percentages of Fe content are indicated on Y-axis for all graphs. Important alloying elements are C, Si, Mn, and Cr while the detrimental elements are P and S.

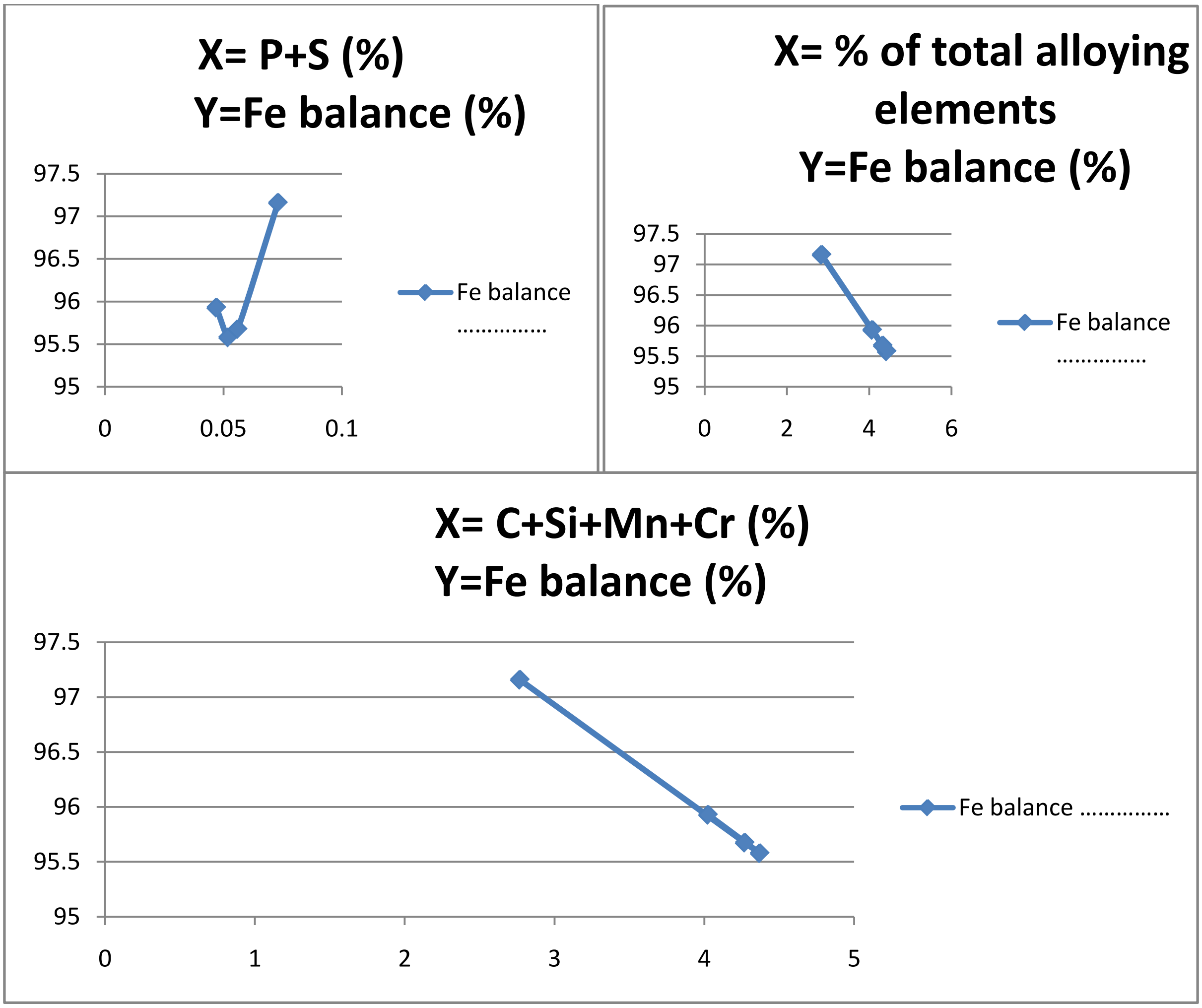

Fig. 11 : Graphical expression showing the fall of composition of the main alloying elements and rise of the detrimental elements along the test stages

The experimental observation for chemical composition of the raw material, the as forged, and heat treated final product of steel ball, is compared with the standard one as in the above table (Table 4) and above figure (Fig.11). The decarburization and oxidation of the main alloying elements resulted in decreasing their content and the necessary hardness and strength of the final ball. The percentage of undesirable elements, S and P, has also increased little bit at the final product which causes the hot and cold shortness respectively.

The main reasons for the problems observed from the metallographic structure and chemical composition of the forging done in the target industry, Akaki Basic Metals, are:

- Heatd billet is highly exposed to open air,
- Uncontrolled temperature of heating furnace and heat treatment furnace atmosphere and,
- Uncontrolled soaking temperature during quenching.

VI. Conclusion

As solving the problem addressed by this research is very crucial for the target industry as well as for the nation, one progress of identifying the root causes for the defective balls are well done. The current product of, mill grinding steel ball for cement industry, the target industry is rejected as defective since it has surface cracks, oxide scales, internal cracks, surface folds, and others. Up to the forging stage the chemical composition of the balls is with within acceptable levels. While heat treatment due to the faulty heat treatment process, without temperature and furnace atmosphere controls, serious deviations occurred in chemical composition particularly carbon content and chromium content resulting in total rejection of the product and its properties. Even the microstructure of the product after heat treatment is with lot of ferrite which is soft phase. After this conclusion about the existing conditions of the defective product the following solutions are recommended. (1) The industry has to fix temperature as well as atmosphere controls for the furnaces while following the standard rules for the furnace temperature, soaking time, and selection of the right quenching media corresponding to the forging material. (2) If some modifications are possible in the industry, after forging of the balls and removing flashes, immediate quenching of forged balls in oil and tempering should be done in forging section.

VII. Acknowledgements

I am grateful to thank the staff members and workers of Akaki Basic Metals Industry that provided for me a convenient condition to identify the stated particular problem and the laboratory equipments for the tests I conducted.

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