Sequential Improvement of Quenching-Self-Tempering-Thermal-Treatment Rolling Process for a Modern Manufacturing System -A Case study

Atul Modi
Department of Industrial and Production Engineering
SGSITS, Indore, M.P, India

D.A. Hindolia
Principal, JNCT,Bhopal,M.P, India

Ravikant Sharma
Department of Industrial and Production Engineering
SGSITS, Indore, M.P, India

Abstract- A modern manufacturing system for steel rolling plants is involves high energy consuming process which is also performed in sequences. In order to save the rolling heat and process primary energy, different thermal-in-line-treatment operations are also performed. Similar to rolling deformation process all theses in-line-treatment are also performed as sequences of operation. A methodology which optimizes the all rolling sequences and in-line-thermal-treatment sequences from daily inputs variability is essential for rolling manufacturing system performance improvement and control. The optimum output can be obtained in current situation by optimum quality, set-up-time, defects and performance for the rolling daily output results.
Keywords – Sequential optimization, In-line-Thermal-treatment, , Modern Rolling manufacturing system.

I. INTRODUCTION

The Modern rolling mill requires very rigid construction due to large reduction ratio, large motors to supply enough power for them and successive stands of a large continuous mill and huge capital investments for quality steel rolling [3]. The high rolling speed, high product quality and good layout, maximum plant utilization and mass production are the main features of any good modern steel plant. In order to determine precise mechanical equipment and processing necessary for optimizing the microstructure, more sophisticated models for microstructure evolution are needed. [20].

Industrial sector is the largest user of energy in India and many parts of the world. The iron and steel industry are capital and energy intensive and serve as driving force for country industrial development [18]. The developing country like India always face problem of resources like energy for targeted increased steel production. In the most recent years, the need for a more rational and efficient use of energy has emerged as a strategic and urgent issue [7]. Every country whether developing or developed is uncertain about energy and its future availability [10].

II. ROLLING PROCESS

The steel rolling is a series and sequence of progressive steps through sets of counter-rotating roll to elongate the material in plastic condition in specified direction to obtain the desired shape and size and to improve the mechanical properties also [19]. Rolling is a metal forming process in which metal stock is passed through one or more pairs of rolls to reduce the thickness and to make the thickness uniform as shown in figure-1.

Hot rolling is used mainly to produce sheet metal or simple cross sections, such as rail tracks. Other typical uses for hot rolled metal includes truck frames, automotive wheels, pipe and tubular, water heaters, agriculture equipment, stampings, compressor shells, railcar components, wheel rims, metal buildings, railroad-hopper cars, doors, shelving, discs, guard rails, automotive clutch plates.

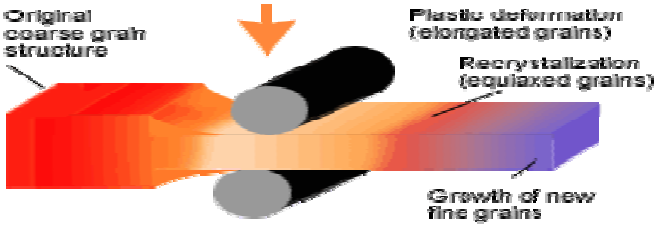

Figure-1 Hot rolling process

The steel market flexible demands changes several times per day for steel rolled product quality and product mix [16]. The economy in rolling or high yield and low cost per ton with consistent quality is always the main or final criteria of rolling [6].

III. REINFORCEMENT BAR ROLLING

Rebar are ‘‘hot rolled’’ from steel billets and subjected to on-line thermo mechanical treatment in three successive stages. Conventional hot rolling takes place in the austenitic transformation temperature [15].

Figure-2 Steel billets & Reinforcement bars

Thermo mechanical rolling is a temperature controlled rolling in different passes. Here the finish rolling temperatures are somewhat lower (Temp. range 800° – 900°C) than during normalizing rolling (Temp. range 1000° - 1200°).The material recrystaliizes no longer in this temperature range and high strength, excellent toughness and optimum weld ability is obtained. This gradually leads to a finer-grained microstructure of the bars which is not possible with normalizing rolling. TMT (thermo-mechanical treated) rebar is appropriate material for reinforcing concrete structures on accounts of similarity in thermal expansion, ability to bond well with concrete and, above all the ability to shoulder most of the tensile stress acting on the structure and also steel manufacturing industry has successfully developed a corrosion-resistant variety of rebar for the construction industry [5] .

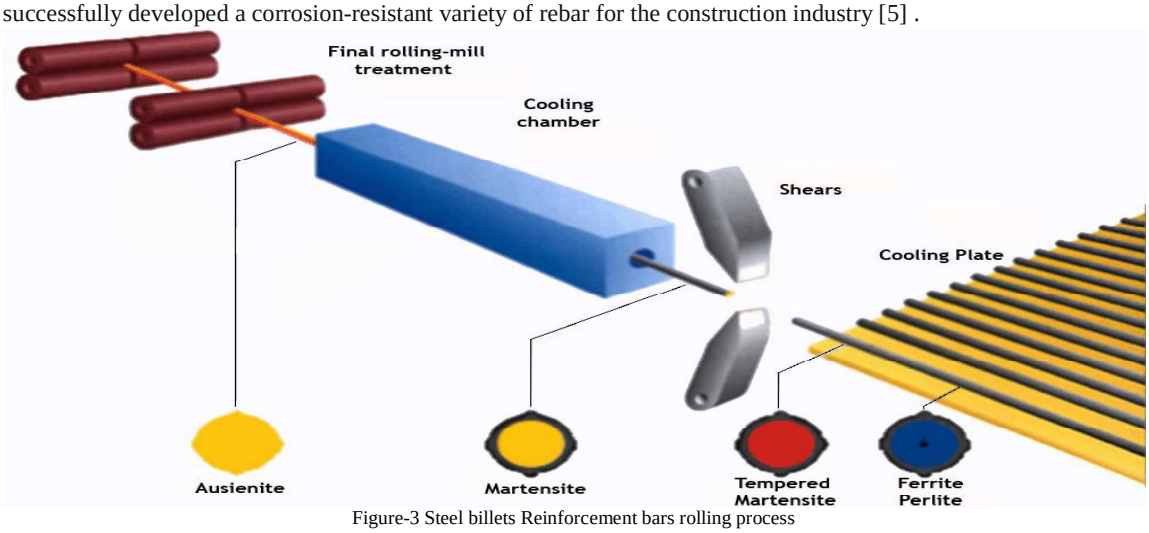

Figure-3 Steel billets Reinforcement bars rolling process

The Figure-3 represents steel billets Reinforcement bars rolling process in a modern rolling manufacturing system. Tension behavior of quenched and self-tempered composite reinforce steel bars is tested at high strain rate [4].

Gribniak et al.(2013), uses finite element software ATENA to analysis RCC structure. As an alternative it is possible to carry out the final forming process at low temperatures ranging between 650 and 750°C. This achieves high strength at low toughness levels

IV. QUENCHING-SELF-TEMPERING-THERMAL-TREATMENT ROLLING PROCESS

The reinforcement bars are produced by direct quenching and self-tempering process from the heat of rolling. Hot rolled bar leaving the final mill stand is rapidly quenched by a special water spray system. This hardens the surface of the bar to a depth optimized for each section through formation of martensite rim while the core remains hot and austenitic as shown in figure-4(a). In self-tempering the bar leaves the quenching box, the core remains hot compared to the surface. The temperature difference allows heat to flow from the core to surface causing tempering of marten site to ‘‘tempered martensite’’. The core still remains austenitic at this stage. At atmospheric cooling which takes place on the cooling bed, the austenitic core is transformed in to ductile ferrite–pearlite structure. The figure-4(b) represents the water cooling system for Thermax system or modern manufacturing system (Moriya) [12].

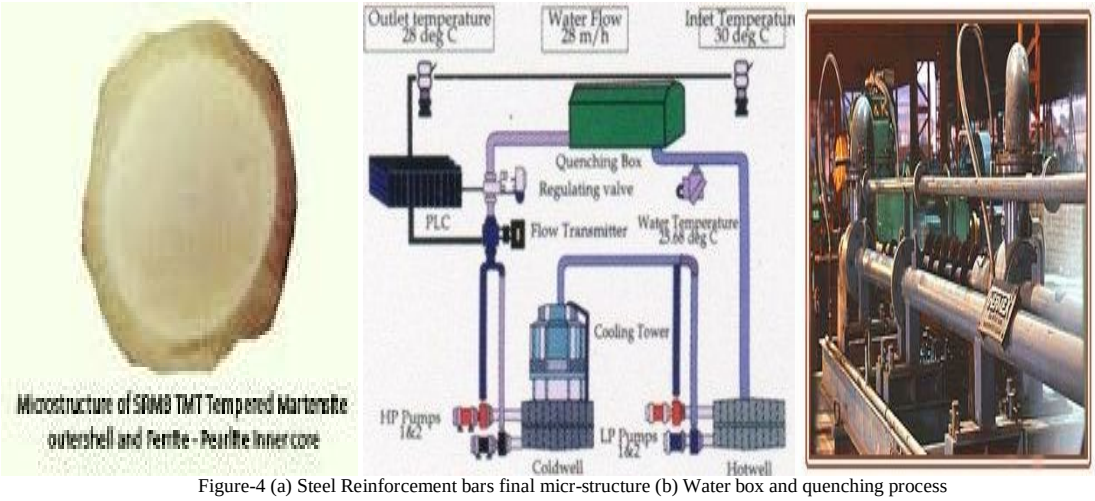

Figure-4 (a) Steel Reinforcement bars final micr-structure (b) Water box and quenching process

V. IMPROVEMENT IN ROLLING PROCESS

The reinforcement bar is the finish product, thus proper control of rolling parameters and water box is needed to achieve adequate property. Water box plays an important role for achieving the final structure and property of the rebar. The temperature evolution is dependent on strain, strain rate, area-reduction, heat transfer coefficients of materials, as well as friction conditions at the roll/material interface, etc., and all of these variables also strongly affect rolling force and torque [11]. The steel market is volatile market with last minute change for order, which demands increasingly closer tolerances on finished products diameters, better yield and predicting higher plants availability by reduced down time and delays [1]. Large number of ways is used to increase the system efficiency like installation of new process equipment, and process improvement. In order to determine precise mechanical equipment and processing necessary for optimizing the microstructure, more sophisticated computer models of deformation and microstructure evolution are needed [7].

Aram, et al, (2013), develop the information flow process model for concrete reinforcement performance improvement over its supply chain [2]. Das et al., (2014), indicate that modern manufacturing system operating system like water box for thermo-mechanical-treated(TMT) re-bars causes variation in outer rim (causes increases in the yield strength of the bars) and resulted into premature failures in brittle manner of bars [5]. The table-1 indicates the different energy forms role in quenching-self –tempering process.

Table-1 Different energy forms role in quenching-self –tempering process

Energy Transfer forms	**Thermo-Mechanical Treatment Processes**
Conduction	Between bar to surrounding &cooling water &injector, inside the bar
Convection	Forced air convection &natural convection cooling of bar
Radiation	Bar to surrounding atmosphere

Metallurgical	Allotropic transformation of material structure of bar

VI. ROLLING PROCESS OPTIMIZATION BY TAGUCHI METHODS

The performance and quality are the most patent tool to improved manufacturing system and right attitude, team work and opportunity exploring may be support them. The performance of manufacturing can be improved by adjusting the inputs set point. A systematic and efficient way to meet these challenges is the Taguchi method (TM). This is also known as robust engineering by design of experiments. Taguchi said, "Robustness is the state where the technology, product or process performance is minimally sensitive to factors causing variability. The Taguchi concept of robust design states that products and services should be designed with an aim that, they are inherently, defect free and of high quality.

The Taguchi defines quality new concept from achieving the specifications, to target oriented performance when applied to the conventional or modern rolling plant then by target oriented production and quality the losses of the plant may be minimized and plant profit will be maximized. The requirements are to deliver a high quality product at low cost which consist of operating, manufacturing and R & D cost [14].

The Taguchi method is a problem solving and performance improvement tool, which improve the results of the product, process, design and manufacturing system outputs. The plant improvement can be obtained by Taguchi target oriented concept which is also called the goal post model emphasis on minimum or zero variation from specifications for all set-up time.

The optimization of manufacturing system means to determine the best architecture, the best parameter value for the best tolerances. The P-Model as shown in figure-1.2 is very useful to control the all type of performance variation of a steel manufacturing system. These methods focus on improving the manufacturing processes and products [17]. Indian modern plant also suffers from high manufacturing cost due to technology dependency, man-power irresponsible behavior and daily performance variations [13]. The reproducibility is the main lagging factor for any type of steel rolling plants. Ylva and Malvin (2014) suggest cost efficient alternative manufacturing forming method by different experiments [9].

VII. QUENCHING-SELF-TEMPERING-IN-LINE-TREATMENT (TMT) PROCESS OPTIMIZATION

Steel Rolling different processes was influenced by many parameters depends on particular sequence. Water box is responsible for outer rim formation and which helps to achieve the yield strength of the material. Rebars were over-quenched in water box due to mismatch in mill speed and water flow through water box which resulting to premature failure during bending operations. The in-line-Treatment is considered as best Technique to use and save process or rolling heat. By this method the production primary energy is used for next post processing operation. Rolling energy cost is divided mainly into furnace fuel cost and electrical energy for rolling deformation in different mills. Cost to benefit analysis is essential to evaluate the energy conservation potential. The energy consideration is most important considerations which included the other considerations and final manufacturing cost also.

The TM applications as used earlier where for mainly for design or for process parameters selections not to optimized the complete production system. This may be useful to obtain the better performance of system and a flexible production system which is capable to handle variability may be obtained. Also the all techniques of TM with other models can be used for manufacturing system optimizations which is essential in current fluctuating time.

The Thermo-mechanical in-line-Treatment process is also influenced by different considerations as shown in figure-5.

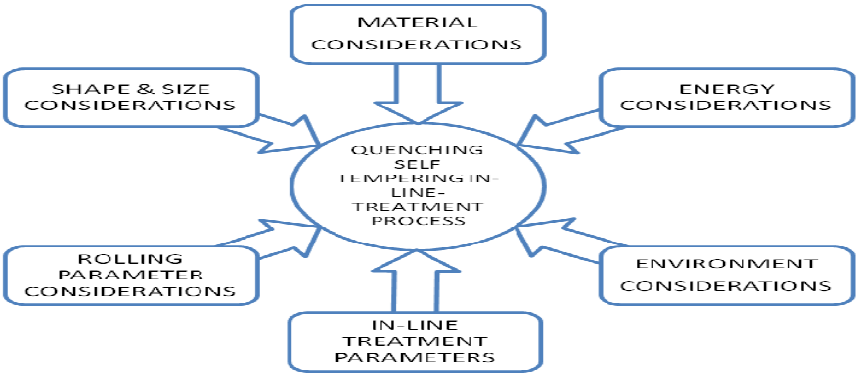

Figure-5 Different considerations for Steel Reinforcement bars rolling process optimization

VIII.MEHTDOLOGY

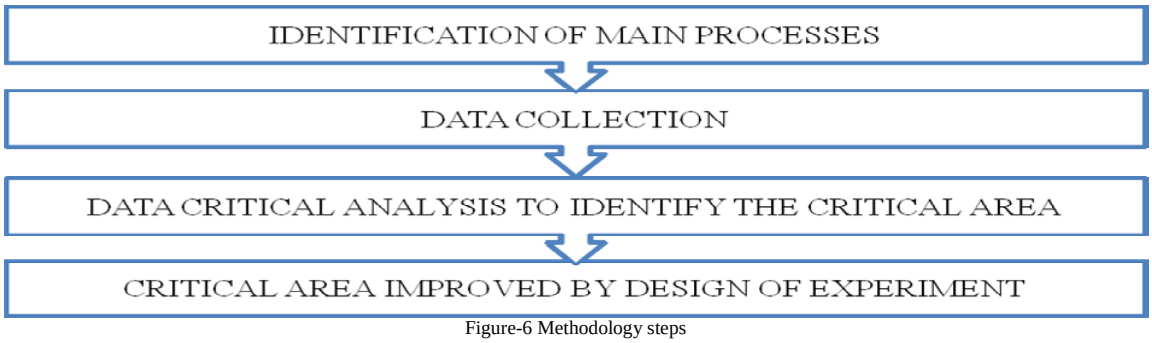

Figure-6 Methodology steps

IX. CASE STUDY

In this case study a steel mini steel rolling plant with hot charge is considered. The concept of mini steel plant is to melt the iron scrap, continuous cast the billets and these billets after cutting into required length directly rolled in the rolling mill, thus save the reheating process as employed in the conventional steel rolling plants. The energy required to extract the iron ore is thus saved and energy required for rolling reheating process is also saved. In this way a considerable energy is saved. The continuous cast machine cast the billet, slab or net shape casting depend on shape of rolling product as round, square, plate or other section like beam, channel etc. The rolling mill produced thermo-mechanical (TM) treated bars in different size and grades. The steel rolling plant throughout the world uses conventional or manual and modern or automatic system or technology and equipment and the mini-steel-rolling plant is state-of-art-technology system. Rolling is most widely used metal working process for reinforcement bars production. To obtain finished product different steps and operation are needed.

X. CONCEPT AND LAYOUT OF MAIN PROCESSES

The mini-steel-rolling plant consist of arc furnace, continuous casting and the hot rolling mill to save billet and process heat by direct hot charging. The mini-steel-rolling plant is a resource based energy intensive industry, as huge energy is consumed and they are the major emitters of greenhouse gases also. The mini-steel plant is now considered as backbone in the industrial growth of any nation.

The mini-steel-rolling plant work as batch production plant as melted-steel-billets are produced in batches called ‘heats’ of 25-35 M.Tons. Although the batch production produces a diverse array of valuable products, these processes generate substantial quantities of pollution and waste due to energy misuse and losses. Strategies for environmentally conscious manufacturing, eco-efficient production, pollution prevention and green engineering have gained widespread acceptance. The safe, stress and pollution free working or the ergonomics consideration helps to develop a positive working atmosphere in the plants.

The Figure-7 represents the mini-steel-rolling plant of case study. The mini steel rolling plant is the integration of many processes like steel-scrap melting arc furnace, ladle furnace and secondary metallurgy for refining, continuous

billet casting machine, hot charging system and hot rolling mill. The plant is compact and required minimum space and time for each operation. Efforts are made for improvements in mini-steel-rolling plants by introducing modern equipment and its operating systems new approaches for process optimization. The plant needs a robust and flexible dust collecting system also to control the air pollution.

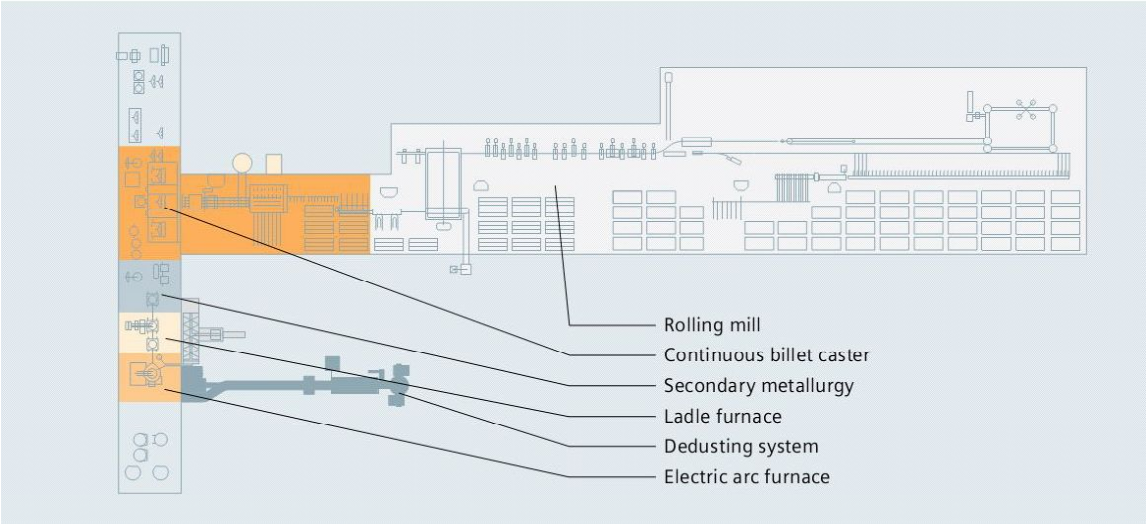

Figure-7 Layout of Mini-steel-rolling-plant and process

In the mini-steel-rolling-plants wastages or losses may be reduced by proper and efficient machinery and tooling and by human skill efficient management. The volatile energy cost and limited resources also force for mini-steel-rolling plant optimization. The inconsistent performance of modern steel plant is a serious problem. The steel industry cannot survive without pollution and emission control. Nowadays, the considerations of environment problems play an important role. In order to eliminate or reduce negative environmental problems, the environmental performance target should be identified and quantified at an early stage or design stage.

XI. DATA COLLECTION

The plant flow process diagram for quenching-self-tempering-in-line-treatment- process is shown in figure-8 as-

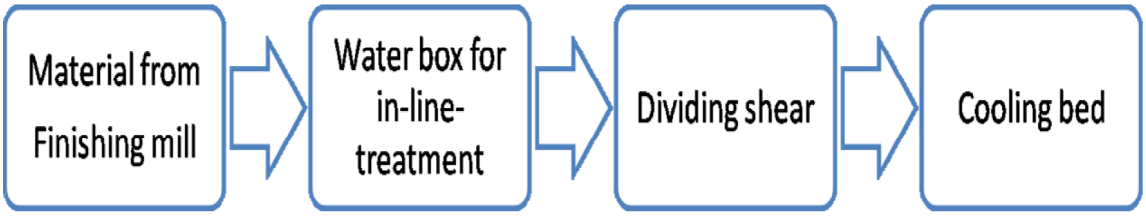

Figure-8 quenching-self-tempering-in-line-treatment- process Flow diagram

The plant data of electricity consumption, % rejection, % miss-roll and yields are for five consecutive years as-

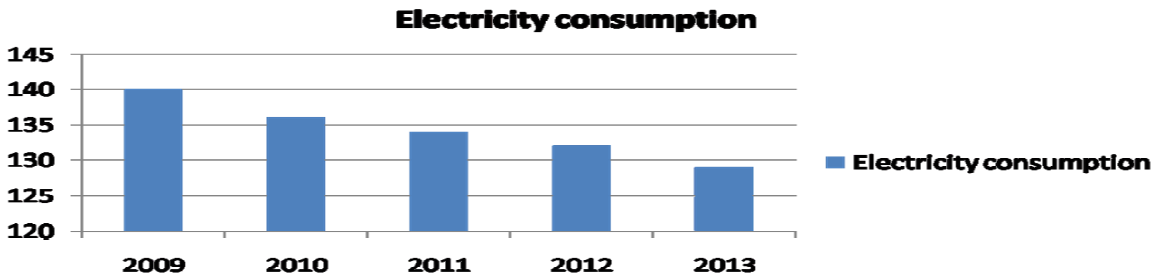

Figure-9 Modern rolling plant electricity consumption

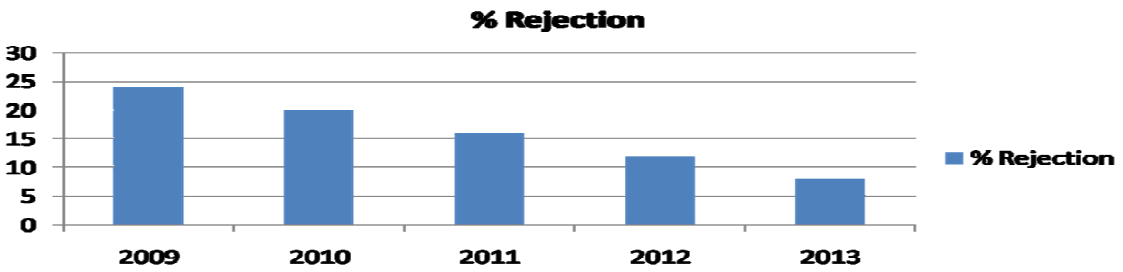

Figure-1O Modern rolling plant % rejection

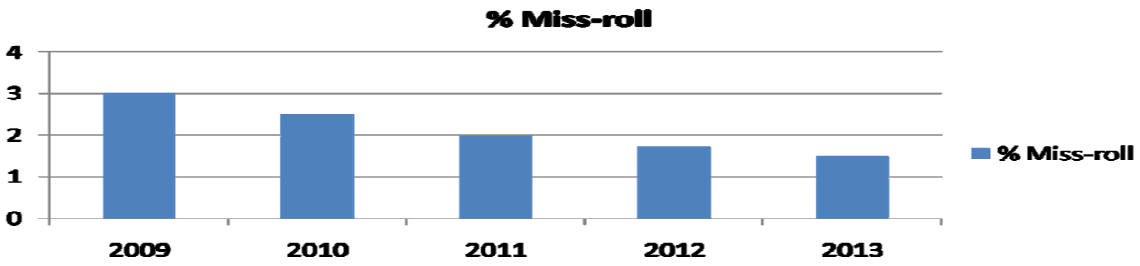

Figure-11 Modern rolling plant % miss-roll

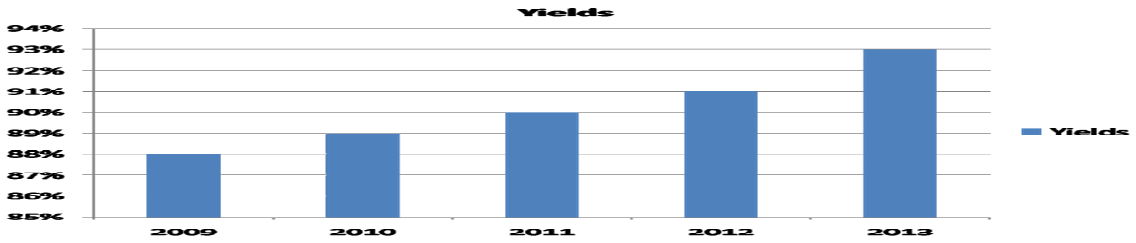

Figure-12 Modern rolling plant % Yields

XII. DATA CRITICAL ANALYSIS

The modern manufacturing system of bar mill is critically analyzed for different functions contributions in delays and miss-rolls as under in figure-13. The TM-in-line-treatment is the critical system in the plant.

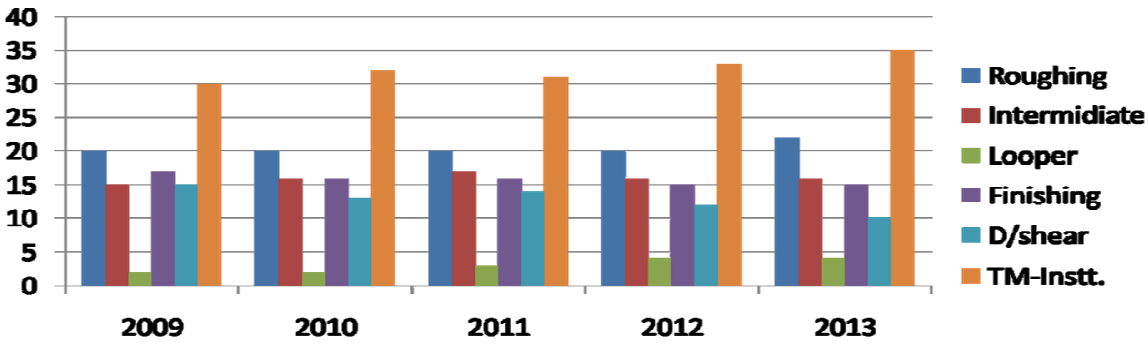

Figure-13 Critical analysis of in-line-treatment-rolling-process

XIII.SEQUENTIAL QUENCHING-SELF-TEMPERING-IN-LINE-TREATMENT-ROLLING-PROCESS

The current demands of steel rolling plants are for the sequential processes, which require small batch production. The rolling process also performs in sequences in different passes. The energy resources wastage due to setting time delays may be minimizes by sequential experiments. The rolling in-line-treatment similar to common rolling process is a sequential deforming process for optimum grain size development.

The high temperature rolling is performed in stable austenite region and material is completely recrystallizes after shaping. The subsequent heat treatment sequence is employed to obtain the specific mechanical properties, which result into process energy loss. The normalizing rolling includes adjustment of material state that corresponds to normalizing. The finishing rolling is done at A3 temperature and material is completely recrystallizes, which is again energy loss. In the quenching-self-tempering rolling the final shaping is carried out in temperature region A3 or just below it. The austenite no longer recrystallizes and results improved grain structure which cannot be achieved by previous rolling methods and lost in heat treatment sequence.

The finish rolling temperature adjustment is very important for fine grain structure and associated properties. The TM rolling is three sequences or steps process as discussed earlier. At the first stage a fast cooling operation applied to the bars inline.. After this quenching, the bar is exposed to air and the core reheated the surface by center heats & tempered the external martensitic in second stage. The third stage occurs as the bar lies on the cooling bed and transformation of core is resulted, the all sequences are to be optimized to get the desired goal by DOE as in figure-14.

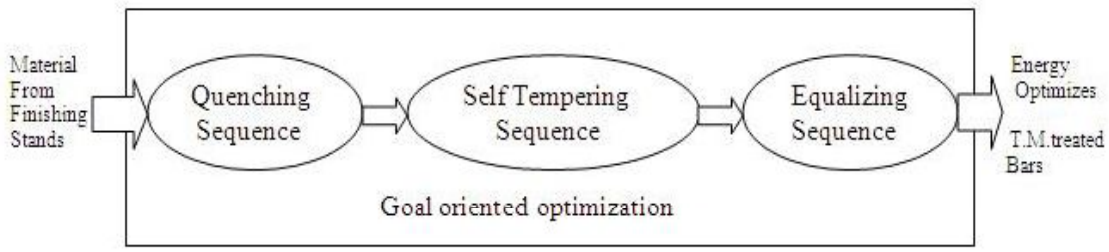

Figure-14 Sequential quenching-self-tempering-in-line-treatment-rolling (TMT) process

XIV. SEQUENTIAL IMPROVEMENT OF IN-LINE-THERMAL-TREATMENT PROCESS

The steel market flexible demands changes several times per day for steel rolled product quality and product mix. The in-line-Thermal-Treatment process was performed in the water box for intensive cooling. The process is sequence dependent activity control by different process parameters and variables. The improvement of process is needed to obtain consistent output as per target output. It starts with data critical screening:-

Data critical screening:-

It is the technique of data screening by considering each and every aspect of rolling process to draw some inferences based on the facts to identify the root causes. The rolling process improvement can be obtained by rolling process

optimization with different considerations as shown in the figure-15. After screening of parameters DOE is applied to treatment process which is also performed in three sequences.

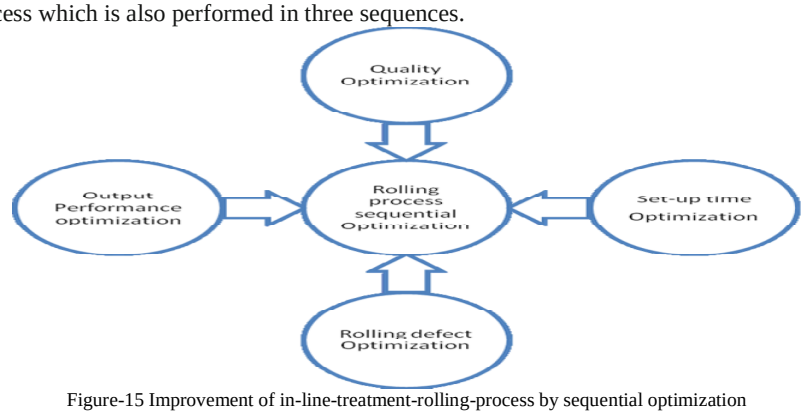

Figure-15 Improvement of in-line-treatment-rolling-process by sequential optimization

The DOE three sequence are:-

Determine that which variable is most important then refine the information by adjust the critical variable to improve the process and then to optimize the process by determine the level o critical variables for best process performance. The in-line-control of rolling variable is best possible and economical tool to obtain the desired results and to develop the new products also. The steel rolling plants operators also faced the problem in effective monitoring and control of process variables like temperature, cooling etc. in absence of proper devices and equipment and but the modern plants has such devices and facilities.

XV. DESIGN OF EXPERIMENTS (DOE) RESULTS

The DOE results with different control factors are calculated and shown in figure-16 to 18 with influence of each factor. The quenching time has maximum influences in all sequences. The improved strength along with toughness and minimum variations of products both within and piece to piece demands consistent output.

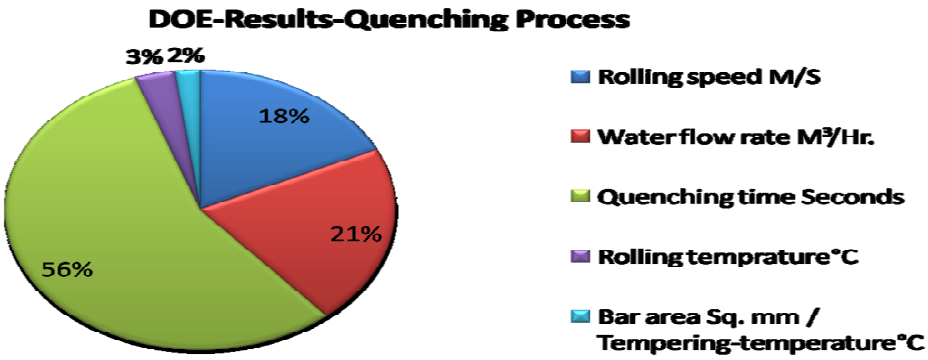

Figure-16 DOE results for in-line-quenching process

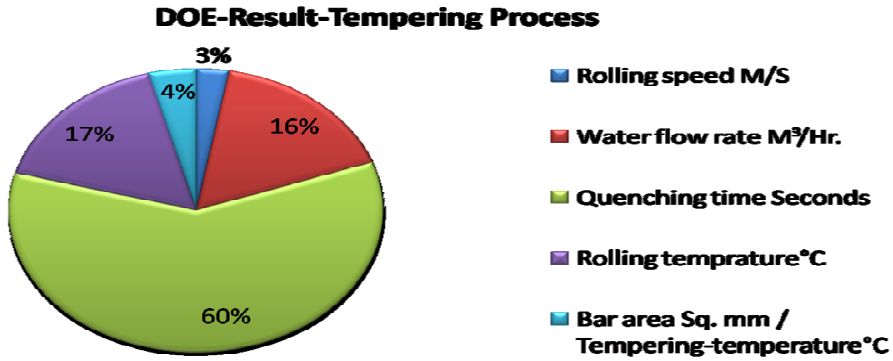

Figure-17 DOE results for in-line-self-tempering process

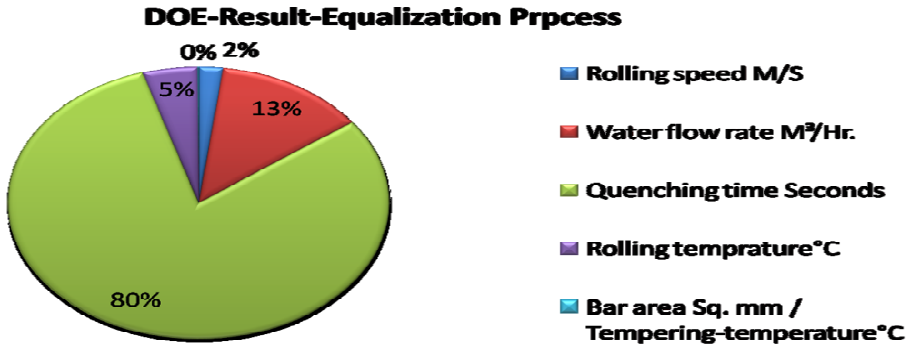

Figure-18 DOE results for in-line-equalizing process

The sequential DOE result indicates that quenching time is the most influential parameter for complete in-line-treatment process and figure-19 indicates the % contribution for all three sequences as under-

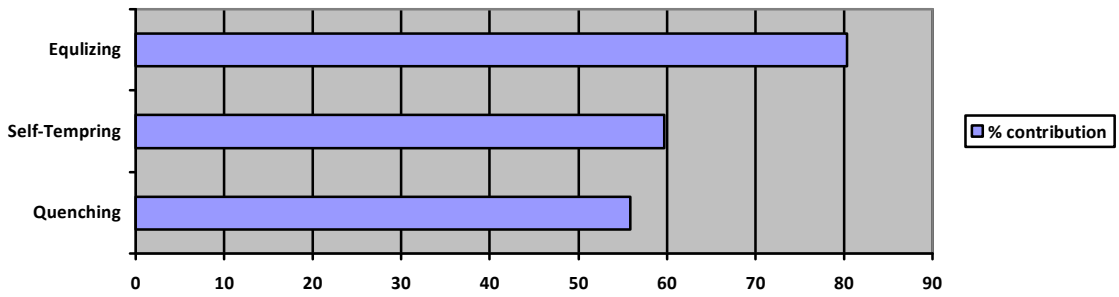

Figure-19 DOE results for % contribution of quenching time for sequential-in-line-treatment process

XVI. IMPROVED MODEL DEVELOPMENT

The rolling process involves sequences of activities. The design of experiment used sequentially so that screening of control variable is done to determine most influential variable for the process. It helps to reduce set up time and cost and target oriented performance as shown in figure-20.

Figur-20 Optimum quality for reinforcement bars

The subsequent experiment is used to refine the information and required adjustment to optimize the process. The modern plant also needs small lot production also. The outcome of design of experiment result into a robust quality or performance that is under different conditions it work well that is the reinforcement bar quality is set on safer side to obtain robust performance. The improved model is developed for current requirement as in table-2.

Table 2: TM In-line-Treatment Process Energy Optimization for reinforcement Bars for Modern Bar Mill.

S. N.	Heading	Possible requirements and problems	Possible solution	Final outcome
1	Optimum performa nce	Bars of different composition, different input parameters of temperature, speed, cooling installation, diameters, water temperature and different cycle of treatment	Optimum input parameters setting of cooling bed, dividing shear and use of variable speed roller table for best performance of bars	Trouble free, uniform and continuous bars for slow cooling
2	Optimum Quality	Variation in martensitic layer and its tensile properties due to improper cooling in equalizing cycle	Rolling bars gap and speed setting, optimum quenching and self-tempering cycle, Dividing shear speed and cut length setting	Best equalizing of martensitic layer by slow cooling of bars
3	Optimum Defects	To remove possibility to develop defects by roller table, cooling bed and dividing shear and hardness, off-grades etc. minimum problem due to roller table, cooling bed and dividing shear	The optimum parameter setting of input parameters and optimum setting of dividing shear, roller table and off-grades with flexibility	Minimum defects due to shears, roller table and TM installation
4	Optimum Set-up-time	Problem developed for mass production of different size for maximum plant utilization and slow cooling cycle	By optimum parameter setting, different ranges for different size of the bars, and optimum quenching cycle and steel composition	Best cooling bed, D/Shear and in-line installation performance

XVII. CONCLUSION

The TM in-line treatment is already used and proved technology but it sequential optimization add different feature in the treatment process. The short cooling bed, high speed, material defects and high % of C are undesirable or noise factors. The in-line-treatment process is control by in-line-control of most influential variable e, g, the quenching time which is energy intensive in nature, as control and related with rolling temperature.

The modern steel rolling plants recent requirement forces for optimal manufacturing cost combined with metallurgical quality of rolled products. However during in-line-treatment design no specific criteria is taken for process optimization. The high energy cost in steel rolling plant now needed to reduce the post processing cost or heat treatment after deformation in rolling. The Validation of results of improved model by in-line-control of temperature is not only useful for same grade and for new grades development also. No one process is perfect but need continuous improvement for changed values of input. In order to develop results on targets the man-machine interactive model is better & most suitable in all conditions.

XVIII. ACKNOWLEDGMENT

We are thankful to **M/S Jaideep Ispat & Alloys Pvt . Ltd**. for support and facility for experiments for the above research work.

REFERENCES

[1] Aksenov, S.A., Fabik, R., Kliber, J. and Kotas, M., Slab FEM Simulation of Hot Bar Rolling, Hutnik, 75, 8, 458–460, (2008).
[2] Aram, S., Eastman, C., Sacks, R., Requirement for BIM Platforms in The Concrete Reinforcement Supply chain, Automation in Construction, 35, 1-17(2013).
[3] Belzunce, F.J., Ziadi, A. and Rodriguez, C., Structural Integrity of Hot Strip Mill Rolling Rolls, Engineering Failure Analysis, 789–797, (2004).
[4] Cadoni, E., Dotta, M., Forni, D., Tesio, N., Albertini, C., Mechanical Behavior of Quenched & Self-Tempered Reinforcing Steel in Tension Under High Strain Rate, Material science & Design, 49, 657-666,(2013).
[5] Das, S., Mathur, J., Bhattacharyya, T., Bhattacharyya, S., Failure Analysis of Re-Bars during Bending Operations , Case Studies in Engineering Failure Analysis, 2, 51–53(2014).
[6] DongSheng, Q. and Lin, H., Blank Design Optimization for Stepped-Section Profile Ring Rolling, Science China Technological Sciences, 53, 1612–1619, (2010).
[7] Ferretti, R., Zanoni, S. and Zavanella, L., Energy Efficiency in a Steel Plant using Optimization Simulation, International Journal of Production Research, 12(2), 171-184, (2009).
[8] Gribniak, V., Cervenka, V., Kakalauskas, G., Defelaction Prediction of Reinforced Concrete Beam by Design Code & Computer Simulation, Engineering Structure, 56, 2175-2186,(2013).
[9] Larberg, Y., Akermo, M., In-Plan deformation of Multi-Layered Unidirectional Thermo set Prepreg-Modlling & Experiment Verification, Composites Part A, 56, 203-212,(2014).
[10] Madhavan, N., Balasubramanyam, K.R. and Punj, S., The Shock around the Corner, Business Today, 7th August, 48-56, http://www.businesstoday.in, (2011).
[11] Meirong, S., Qingxue, H., Jianping, Q. and Yanchun, Z., Analysis of Mechanical Parameters during Hot Continuous Rolling Process of Titanium Alloy TC11 Rod, Rare Metal Materials and Engineering, 0952-0957, (2012).
[12] www.Moriyasariya.com.
[13] Pathak, P., Singh, A.P., Rai, D., Roy, B. and Jha, S.K., Tribological Approach for Improvement in Surface Quality of Hot and Cold zolled Steel Strips, International Journal of Manufacturing Technology & Research, 7, 1, 93-100, (2011).
[14] Phadke, M.S., Quality Engineering Using Design of Experiment, Prentice-Hall, Englewood Cliffs, New Jersey. USA, (1991).
[15] Phaniraj, M.P., Behera, B.B., and Lahiri, A.K., Thermo-Mechanical Modeling of two Phase Rolling and Microstructure Evolution in the Hot Strip Mill Part I. Prediction Of Rolling Loads And Finish Rolling Temperature, Journal of Materials Processing Technology , 323–335, (2005).
[16] Shatalov1, R.L., and Genkin, A.L., Operating A Sheet-Rolling Complex to Minimize Energy Costs, Metallurgist, 52, 485-490, (2008).
[17] Tahmasebipour Gh., Hojjat Y., and Abdullah A.A., Optimization of STM/FIM Nanotip Aspect Ratio Based on the Taguchi Method, International Journal of Advanced Manufacturing Technology, 44, 80-90, (2009).
[18] Thangavela, S., Palanisamy, V., and Duraiswamya, K., Genetic Based Sensorless Hybrid Intelligent Controller for Strip Loop Formation Control Between Inter-Stands In Hot Steel Rolling Mills, ISA Transactions, 179–188, (2008).
[19] Trinks, W., Roll Pass Design, The Penton Publishing Company, Cleveland, Ohio, (1949).
[20] Wang, L.P., Lian , J.C., Wu, X.D., and Jiac, X., A New Rolling Force Model for Dry Thick Temper Rolling Strip Mill, Journal of Materials Processing Technology, 381–384, (2005).