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Steel Re-Bars In-line Treatment Process Optimization by ANN-DOE Modeling

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***Abstract*— Modern steel rolling is material deformation process to achieve desired shape and metallurgical results of reinforcement bars under influence of different variables. This also includes generation of optimum defects such as dislocations, vacancies and imperfections density in crystal structure through thermo-mechanical-in-line-treatment. To obtain desired mechanical properties optimization of developed defect is essential. Rolling manufacturing performance variation control under influence of different variables is essential for desired results. Process optimization, such as thermo-mechanical-in-line-treatment is essential to save process high energy cost in re-bar manufacturing. ANN-DOE modeling is used for optimization. Five controlling factors were varied at two levels to obtain S/N ratio as performance output and characteristics. Rolling processes sequential optimization has been applied to get improved model by the help of Artificial Neural Network (ANN) and Design of experiments (DOE) applications.**

***Keywords*— Rolling process heat, Micro-structure, Energy and Defect optimization.**

I. Introduction

The behavior of high strength reinforcement re-bars are becoming an important issue due to extensively used basic construction material throughout the world. Thermo Mechanical Treatment (TMT) is a useful technique in re-bars manufacturing to saves costly micro-alloying addition and for improvement in micro-structure and tensile strength by increase in density of defects and optimum structure. Novikov I., [1974], consider, TMT is type of in-line- heat-treatment during plastic deformation after finish-rolling to increases the density of defects as dislocations, vacancies, stacking faults, high angle boundaries in the crystal structure for optimum structure in re-bars.

Plastic deformation changes the pattern of distribution and increases the defect density. Frantz et al. [1989] insist that the TMT is a well-tested energy loss control process to reduces manufacturing cycles and resources consumption saving. Hot deformation increases the density of lattice defects and produces hot strain hardening and softening effect continuous or alternate for improved re-bars mechanical properties.

According to Simon P., [1990], the re-bar structure is a mixture of ferrite, pearlite and bainite with varying percentage, depending on several factors affecting the phase transformation after rolling simultaneously. Goryany and Radsinsky [2002] emphasizes that the modern steel re-bars plant also suffers from high manufacturing and energy cost due to performance variations of equipment and daily variations of quality. Ferretti et al. [2009] conclude that reduced resource consumption for rolling process energy and heat saving can be achieved by efficient and optimum in-line-treatment cooling installation.

Balogun et al. [2011] consider, that the re-bars mechanical quality like flow stress, strain-rate and re-crystallization are obtained in better way during rolling-in-line-treatment. While Saravana kumar et al. [2012] uses ANN model to predict the mechanical properties of re-bars for in-line-thermo-mechanical treatment process. Hara and Azushima, [2014] insist to reduce oxide scale developed during hot rolling for improving productivity and yield. Altinkaya et al [2014] preferred ANN modeling due to its versatility for rolling manufacturing system and energy loss control. At present time an optimum TMT process is needed as defect-optimizer, simultaneously after rolling to saves process energy considerably and conserved the costly resources by reducing its losses.

II. Rolling Processes Modeling

Artificial Neural Network is an advanced data mining tools useful for complex manufacturing like rolling deformation process. The biologically inspired modeling tool provides better statistical results with already validated techniques like Taguchi's DOE. The multilayered perceptron neural network architecture is very useful due to feed forward back propagation learning algorithm. Taguchi's DOE, S/N ratios is useful to measure output characteristics.

ANN possesses one or more layers of neurons which are fully or partial interconnected through associated weight.

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In the final step testing of ANN model performance or comparing test results with historical results or Black box testing is done. Errors terms can be used to compare the results.

Simon P. [1990], insist that rolling process different improvement aims are to reduce the manufacturing cycle time for reducing the process energy losses for new grades and sizes. According to Belen'kii, A. M., [2003], energy minimum losses, wastages and parameters optimization, is essential. Zhuchkov et al. [2006], consider that customer now compares the finished rolled product on basis of its post-processing ability and cost. Lutsenkoa et al. [2010] discussed the TMT grain size optimization to improve mechanical properties. According to Genkin A. L., [2011], there are significant energy savings opportunities in the steel production process which are still yet untapped.

Graus and Blomen [2011], consider a high potential for energy conservation by process energy recovery and waste control.

Ohara et al., 2014, demonstrated that the faster rolling results in a smaller austenite grain size because there is less time for grain growth during rolling. Das et al., 2014, emphasized that the rolled bars sometime indicates variation in cross section microstructure, but have tough, tempered martensite in the re-bar, at intermediate layer different structure as martensite, bainite, ductile ferrite and pearlite at center.

III. Optimization Of Re-Bars-TMT Process

Rolling deformation process is now integrated with defect optimization developed by heat treatment during in-line-process after rolling. Rolling process is needed to eliminate post processing cost and energy losses. TMT process start with a fast cooling operation applied to the bars by quenching as it leaves the last finishing stand. The second and third stage performed as the bar leaves the area of drastic cooling and is exposed to air and occurs on the cooling bed to convert austenitic core into ductile ferrite-pearlite structure. Water box or cooling installation is responsible for required quenching to obtain desired yield and tensile strength.

Model developed by Simon P. [1990] is for optimization of Tempcore installation, which is based on results obtained in more than 25 plants where these system were installed and in use. In Panigrahi [2001] views**,** achievement of a higher degree of consistency in mechanical properties and microstructure is essential for steel rolled products. The mathematical model can also be developed. In Belen'kii, A. M., [2003] insist for energy efficiency for all products including steel.

Van and Amerling, [2004], emphasized that the performance of rolling processes is difficult to control due to the dynamic processes and new customer requirements.

Kanaev et al. [2010] consider that TMT process integrates controlled cooling and heat-treatment process simultaneously to used rolling heat for treatment after finishing for optimization as post processing for optimum results. TMT process essentially performed in phase transformation after rolling for optimum structure than post processing sequences. A number of parameters required to be considered, like water flow rate, range length, numbers of cooling nozzles and safety margin etc. Different criteria are used for optimization of installation and plant whether modern or conventional. The energy optimization is a tool to minimize processes cost and continuous improvement cycle by reducing sequences energy losses.

The marten site volume is best performance measure of in-line-treatment of re-bars. The variation of marten site volume and yield strength is causing variation in re-bars mechanical properties. Reinforcement bar non-homogeneous cross-section is the problem which causes re-bars failure and bar cannot consider as isotropic material. From visual and analysis of electron micrographs results the brittle nature was obtained in some bars as in figure-1.

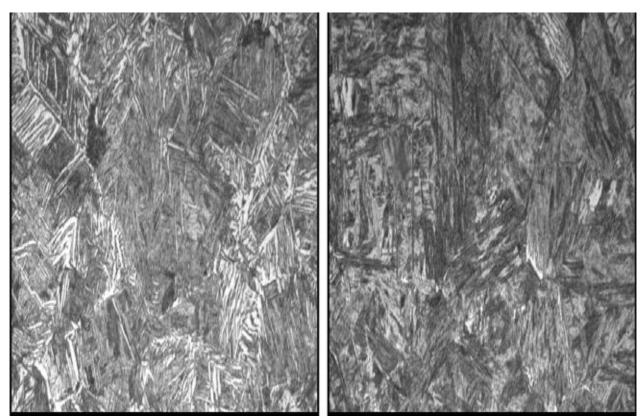

Figure-1 Harden martensitic matrix structure (20 Microns) in center and edge for re-bars

Harden martensitic matrix from center to edge is also formed due to over quenching in which cause failure. The grain boundary in the decarburization region is also oxidized. There is an increased in small diffusional oxides due to high rolling temperature and scale problems.The variation in mechanical properties like, tensile strength and elongation needed optimization of process. The varying cost, rejection and quality variations are other concerns areas of rolling manufacturing system.

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IV. Rolling TMT Sequences Experiments

The rolling process experiments for the in-line-treatment was carried out in three sequences with five inputs and one output i.e. S/N ratio in a reinforcement bars rolling. Different experiments are performed to obtain S/N ratio by DOE during manufacturing and testing for yield strength in a modern steel plant. The S/N ratio obtained from different experiments is used to train the network model with suitable weights adjustment and correction. Some factor like A, D, E are changed in second next sequence due to dominating influence of other factors on process sequence.

Table-1
DOE Parameters and Levels for Quenching-Self-Tempering Process

6	Control factor	Level 1	Level 2
A	Rolling speed, (m/s) / Cooling intensity (mw/m 2)	10	12
B	Water flow rate, (m3/h)	180	210
C	Quenching time, (s)	0.6	0.8
D	Incoming temperature, (°c) / Time on cooling bed (s)	1000/150 s	1020/20 0s
E	Bar area (Sq.mm)/ Tempering temperature(°c)	50\620	52/660

Table-2
Measured Yield Strength for TMT Bars for Quenching

S N	Factor & Column No. A	B	C	D	E	Measured Yield strength, (MPa) 1.5m	3m	4.5m	6m	7.5 m	S/N Ratio
1	1	1	1	1	1	380	378	378	378	378	51.5
2	1	1	1	2	2	385	384	386	386	387	51.6
3	1	2	2	1	1	405	405	403	405	406	52.4
4	1	2	2	2	2	410	412	411	413	410	52.7
5	2	1	2	1	2	408	406	407	405	405	52.1
6	2	1	2	2	1	410	410	408	408	409	52.5
7	2	2	1	1	2	409	410	409	410	410	51.7
8	2	2	1	2	1	407	408	408	410	409	52.2

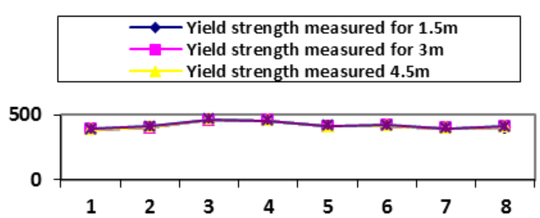

Figure-2 Re-bars yield strength variations at different length in quenching sequence

In order to obtain consistent mechanical properties similar chemistry of billets are preferred.

Measured UTM for TMT bars at different lengths of the bar is shown in Figure-2 for quenching sequence with S/N ratio. The behavior of Re-bars and its yield strength variations in quenching sequence on entire length is same.

Figure-3 indicates yield strength as measured for TMT Bars at different lengths of the bar for Self-Tempering sequence. In this sequence tempering temperature influence is also considered on re-bars. Similar behavior of re-bars found on yield strength variations at different length in Self-Tempering sequence.

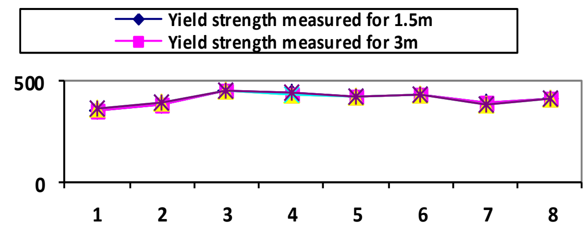

Figure-3 Re-bars yield strength variations at different length in Self-Tempering sequence

Figure-4 indicates the similar behaviour of Re-bars and its yield strength variations at different length in equalizing sequence. The equalizing sequence influence on re-bars entire length is again same.

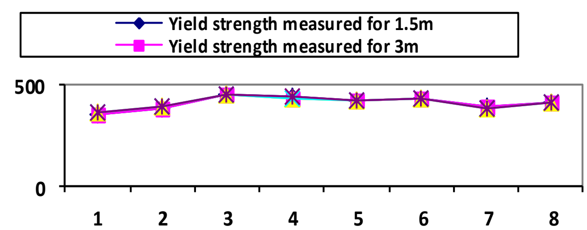

Figure-4 Re-bars yield strength variations at different length in equalizing sequences

Table-3 indicates control factors contribution and optimal value of parameters for quenching self-tempering-equalizing all three sequences. The quenching time is most influential parameter which can control the all three sequences or complete in-line-treatment process. By optimum setting of quenching time the desired performance results and consistent output can be obtained with minimum losses for all grades and size. The metallurgical examination is performed on microscope at 100x magnification. The micrograph is used to determine the grain stricture.

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Table-3
Optimal Parameter Setting for Quenching Self-Tempering-Equalizing sequences

S. N.	Control factor	Optimal value of parameters			% Contribution in sequences		
		Quenching	**Tempering**	**Equalization**	**Quenching**	**Tempering**	**Equalization**
1	Speed M/S	10	12	10	12.1	3.88	2.00
2	Water flow rate M^3/ Hr.	210	210	210	20.83	16.67	12.85
3	Quenching time	0.6	0.8	0.6	55.8	59.7	80.35
4	Temperature ^{0}C	1020	1020	1020	3.33	16.7	4.62
5	Bar area sq. mm / Tempering-temperature ^{0}C	50 / 620	50 / 620	50 / 620	2.08	4.10	0.12

V. ANN-DOE Modeling For TMT Sequences

Rolling processes are very complex and its performance is influenced by different variables. ANN modeling was performed to predict symptoms of Re-bars in-line-treatment in cooling installation with yield strength signal to noise ratio as performance characteristics. The network selected is consists of an input layer, hidden layer and one output layer. The back propagation algorithm was used for repetition process of training and correction of the weights. Feed-forward network was employed with Levenberg-Marquardt back propagation (trainlm) algorithm as the training function. The ANN performance was measured by mean square error (MSE) of actual from predicted S/N ratio for all three sequences.

The TMT sequences ANN-DOE modeling method is very useful to study and generalize the improve model of rolling processes. Figure-5 shows experimental and network's S/N ratio for different sequences of in-line-treatment in the rolling mill.

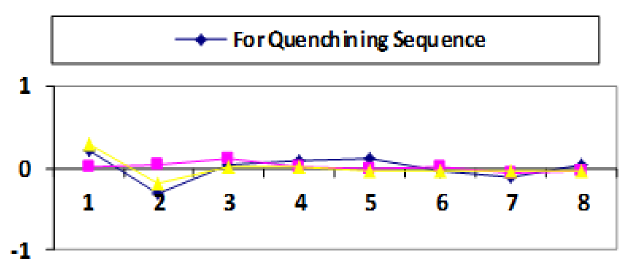

Figure-5 Network error variation during Sequential in-line-treatment

Maximum error variation is for quenching sequence which is less than 0.5% and for other sequence it is less than 0.2%. The ANN-DOE modeling can be also used to develop an equation for process optimization in varying conditions. The quenching time can be used to optimized the complete re-bars rolling process sequences for results.

VI. Validation Of Results

ANN-DOE model results testing are performed in same plant. The improved re-bars rolling process by in-line-control of most influential variable quenching time is validate in the rolling plant for one week for trail.. The experiments are carried out with no change in plant layout and equipment set-up. The desired rolling temperature at various mills sequences is obtained with minimum variation.

The temperature measurement results indicates variation of maximum 15 ^{0} C for various samples during trail rolling. Temperature control is essential from roughing rolling to obtain desired dimensional and metallurgical accuracy in all sequences. The influences of other parameters like compositions, finishing temperature and speed etc. are reduced. The control of temperature starts from hot charging system as shown in Figure-6. The sampling of similar composition billets are performed for different samples A-G from different batches with varying setting.

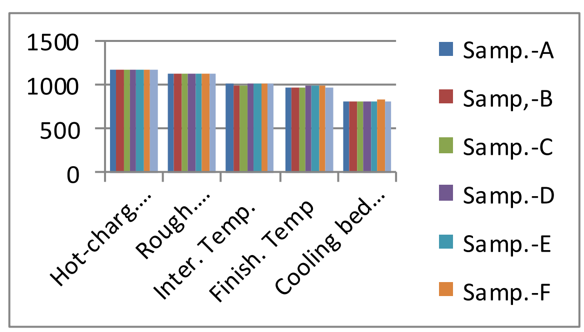

Figure-6 Temperature measured for different samples A-G at different locations.

The process is properly monitored and in-line-controlled as shown in results of temperature measurement of the samples at different rolling cycles. Table-4 indicates Setting of composition, size and tempering temperature as measured by pyrometer etc. for different samples A-G for in-line-treatment sequences.

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Table-4
Setting for different samples A-G for Quenching Self-Tempering-Equalizing sequences

Rolling sample	BarSize, mm	Tempering Temp. 0 C	Carbon %	Manganese %
A	8	600	0.19	0.5
B	8	605	0.27	0.6
C	10	610	0.18	0.5
D	10	608	0.23	0.8
E	10	610	0.21	0.7
F	12	620	0.18	0.5
G	12	615	0.23	0.8

In figure-7, the relationship between yield strength with quenching time as obtained from different samples is shown. The diagram indicates that different bars of different composition and size are obtained the required yield strength. The relationship obtained is linear and the effects of all other variables are minimized.

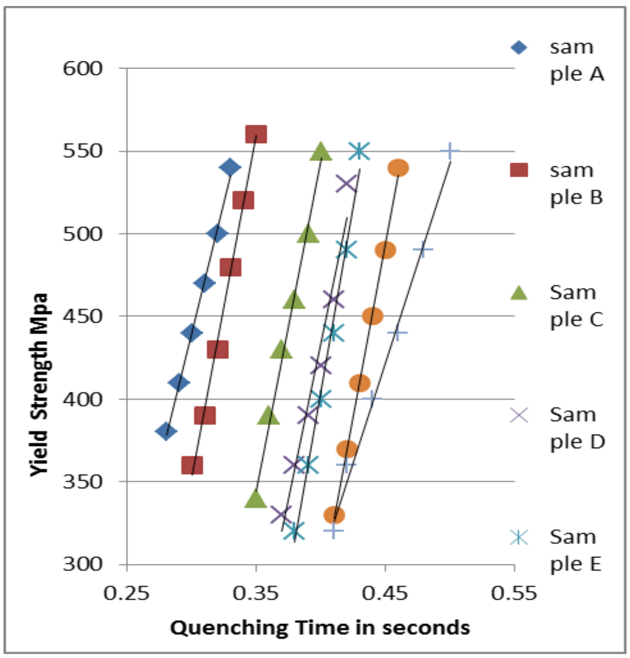

Figure-7, Relationship between yield strength and quenching time

The figure indicates that the optimum % volume of marten-site can be obtain, as shown in Figure-8.The relationship between quenching time, yield strength and % volume of marten-site indicate the re-bars in-line-treatment process optimization by single influential variable, which is energy intensive. Recent requirements of uniform quality, optimum defects and minimum set-up-time and performance variations can be obtained by new model.

VII. Conclusions

Rolling process DOE is performed in modern steel rolling plants. The S./N, obtained from experiment are used to train the ANN. The **neural network architecture** is used for Re-bars defect optimization process modeling and at same time process energy losses control. The generalized results are applicable to different steel rolling plants. Recent requirements of uniform quality, optimum defects and minimum set-up-time and performance variations can be obtained by new model. The Re-bars in-line-treatment process ANN-DOE modeling helps to obtain consistent and optimum mechanical properties. Complete rolling process is simplified and set-up time for new sizes and grades are reduced.

Harden martensitic matrix from center to edge is also removed as developed due to over quenching in cooling installation by optimum parameter setting during in-line-treatment and optimum structure is obtained. Sequential rolling processes are sequentially optimized by ANN-DOE. The reinforcement bars manufacturing increasing energy cost due to quality variations are minimizes. Rolling mills energy wastage as the rejection, different losses, and rework are also eliminated by optimum parameter setting during re-bars treatment process and rolling deformation. The in-line-control of influential control variables is essential to obtain desired micro-structure, mechanical properties etc.

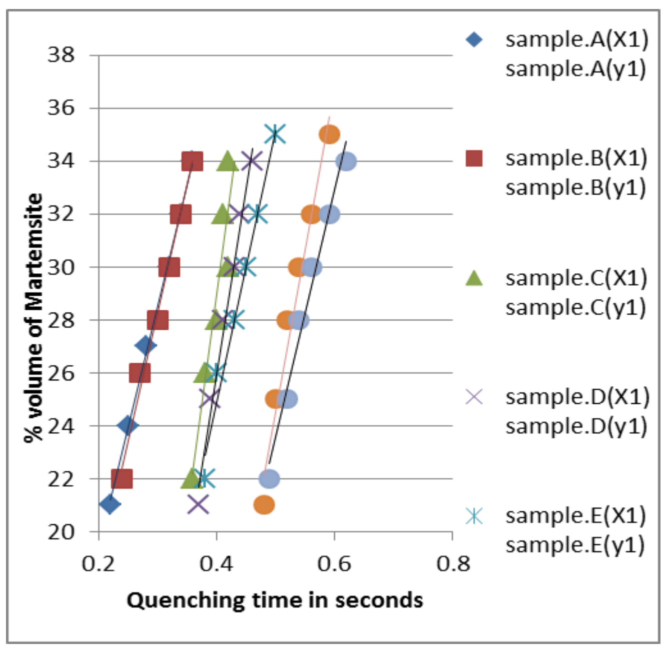

Figure-8, Relationship between quenching time and % volume of marten-site

The neural network computing is a key component to validate and generalized energy optimization by optimum parameter setting of re-bars rolling during in-line-treatment. The manufacturing system used in steel rolling plants is energy optimized by single energy intensive variables. The energy wastage is minimized as target temperature is achieved with hot charging and the billets are preferred without scale by fast speed of conveyors of hot charging system transfer table. Table-5 indicates In-line-treatment process energy optimization improved model with targets for optimum results.

Table-5
In-line-Treatment Process Energy Optimization by Improved Model.

S.N.	Heading	Targets
1	Optimum performance	Optimum cooling installation design for most influential parameter setting for Trouble free, uniform and continuous reinforcement bars
2	Optimum Quality	Optimum quenching time setting and best equalizing of martensite layer by slow cooling of bars at bed
3	Optimum Defects	TM installation most influential parameter best setting for required tempering temperature and optimum defects, cooling bed best setting.
4	Optimum Set-up-time	Optimum material composition, most influential parameter setting for different grades and sizes, Best cooling bed for optimum performance.

The sequential optimization modeling is best to control all types of energy losses by reducing performance variation.

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