Response Surface Optimization of Rolling Process Parameters in Hot Rolling of St60mn Steel

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Abstract

In hot rolled process, the yield strength, tensile strength and toughness play major roll in the structural reliability of the hot rolled steel. Hot rolled St60Mn steel rebars are used for the manufacture of steel for use in construction and other industries. Improved yield strength and toughness of the steel used in construction are often desired to avoid fracture failure and promote impact loading. In this study, Response Surface Methodology was used to study the behaviour of the tensile properties and toughness of the hot rolled St60Mn steel when hot rolled at various finish rolling temperatures and rolling strain rates. The Response Surface Methodology (RSM) was used to investigate the individual and interaction effect of finish rolling temperature and rolling strain rate as independent variables on the yield strength, tensile strength and toughness properties of the hot rolled steel. The St60Mn steel was hot rolled at various finish rolling temperature between 915°C-923°C for rolling strain rates of between 5 x 103s-1- 7 x 103s-1.The influence of the finish rolling temperature and rolling strain rates on the yield strength, tensile strength and toughness were investigated by modelling the relationship using cubic order polynomial to develop the response surface plots and their respective contour plots. The RSM proposes models describing the influence of the rolling process parameters on the properties of the hot rolled steel. The model was able to account for the curvature of the response and the interaction of the independent variables in the response surface. There spone surface methodology (RSM) was applied to optimize the rolling process parameters to attain the optimal values of the properties. The optimized values for the yield strength, tensile strength and toughness for the hot rolled St60Mn steel were obtained as 470.13 MPa,701.63 MPa and 0.458042 joules/mm² respectively. The optimization was achieved within the 95

Index terms— hotrolled, steel; finish rolling temperature ; rolling strainrate; yield strength; tensile strength; toughness; optimization; rsm, model.

1 Introduction

hen a piece of metal is rolled between two rolls, the metal piece experiences both vertical and horizontal stresses caused by the compressive load from the rolls and the restrains by the portions of the metal piece before and after the material in contact with the roll respectively **??**Dutta ,1986).

As the rolls exert a vertical stress on the metal piece, the latter exerts the same amount of stress back onto the rolls itself. As such the rolls are subjected to stresses exerted by the rolls and it is treated as a twodimensional % total deformation in the thickness in length directions or changes its cross sectional area. This deformation influences the mechanical properties of the hot-rolled steel **??**Ashrafi et al,2015).In the deformation zone the thickness of the input metal gets reduced and it elongates. This increases the linear speed of the work piece at the exit.

The contour of the roll gap controls the geometry of the product **??**Dutta,1986).

"Draft", also known as draugth, is a term meant to express the reduction in cross section height / area or reduction in height in a vertical direction when compressed between two rolls. Draft is either direct or indirect.

Indirect draft results when the rolls exert on the stock in non-vertical direction. Basically it is a grinding action between the collars of two rolls rotating in opposite direction.

When part of the pass profile is inclined in between the vertical and horizontal, the % total deformation is caused by a combination of direct as well as indirect drafting.

Up to an inclination of 45°with the horizontal direct drafting predominates. However, above 45° inclinations the effects of indirect drafting comes in to play. Near 90° the % total deformation depends almost entirely on indirect draft ??Dutta,1986).This reducing ratio or draft also affect the mechanical properties and microstructure of rolled products (Aodaet al,2012, ??ong et al ,2004).

"Elongation"in stock length is associated with reduction in area, as volume of metal that leaves the rolls and the one that enters them is equal. Elongation factor, i.e., the ratio of the final length to the initial length is always greater than unity ??Dutta, 1986); and this enlongation decreases as the deformation increases ??Hutchinson et al,2015)."Spread": When steel stock is compressed between two rolls, it obviously moves in the direction of least resistance. There is not only a longitudinal flow but also some lateral flow, which is called 'Spread' ??Dutta,1986).

2 W

Rolling signifies one action but two reactions. The rolls apply a 'reduction' (vertically); this reduction produces an 'elongation' and 'spread' (sideways).

The stock under vertical compression meets some longitudinal resistance to free elongation which assists in causing sideways spread.

Spread is the flow of material at right angles to the directions of compression and elongation.

The higher the coefficient of friction, higher is the resistance to lengthwise flow and more is the spread.

The quantum of spread can never be worked out analytically. Neither any formula nor any method of computation is available to quantify spread.

Roll Designers only rely on guess estimate to overcome the problem, but accuracy of such guess work is not only extremely necessary but is needed. In practice it is found that the following factors affect the amount of spread.

Rolling temperature of the work piece influences spread appreciably. Lower the rolling temperature of steel input, greater is the spread, as well as the strength of the hot-rolled steel. Similarly, higher the rolling temperature, lesser is the spread, as well as the strength of the steel. Also the higher the rolling strain rate, the greater is the spread and the strength of the steel and the lower the enlongation of the hot-rolled steel. The lower the rolling strain rate, the lesser is the spread and vice versa ??Sierakowski, 1997; ??ahker et al,2014; ??ihalikova et al,2007; ??ong et al,2004).Lesser speed of rolling results in greater spread and vice-versa.

Diameter of the working rolls plays a significant role in the guess estimation of spread. Higher the diameter of the working rolls, lesser is the spread. Similarly, lower diameter results in higher spread.

Surface roughness, i.e., friction of the working rolls plays a note worthy part in determining spread. Rougher the roll surface lesser is the spread and smoother the roll surface more is the spread. Stock height and width play influences spread. Higher draft and wider stock signifies greater spread. When rectangular stock passes through plain rolls then the spread is "free" or "unrestricted".

However, if the stock passes through grooved rolls, then the form of the pass keeps the spread within certain limits. This is known "restricted" spread. Because of this restricted spread the width of an entering stock is smaller than the width of the pass groove.

It is accepted that beyond a ratio width / height = 5, spread becomes negligible ??Dutta,1986).

An investigation on the optimization of hotrolling process parameters in bar and rod rolling of Fe-500 and high alloy steels using gleeble temperature profile, strain, strain rates and temperature in roughing and finishing stands lead to defect free rolling (Kumar et al.,2012).

A mathematical model which consists of sub models for static and metadynamic recrystallisation, grain growth and the transformed ferrite grain size that were characterised for a wide range of C-Mn and HSLA steels, has been developed. It predicts the final mechanical properties of hot rolled steels, and is suitable for the evaluation of new steel grades and the development of optimised thermo mechanical processing routes ??Hodgson et al,1992).

In this present study, the combined influence of the finish rolling temperature and rolling strain rates of the hot rolled St60Mn steel is discussed. The yield strength, tensile strength and toughness of the hot rolled St60Mn steel are developed as functions of the finish rolling temperature and rolling strain rates using the response surface methodology (RSM).It is desired to investigate how much of influence the finish rolling temperature and rolling strain rates affect the property response of the hot rolled St60Mn steel and to find the combination of these rolling process parameters that will provide the optimal response of the properties.

3 II.

4 Methodology

Rolling cycles of St60Mn steel billets which were charged into the furnace and heated to the rolling temperatures in the range 1150°C -1250°C and later rolled into 12mm,14mm,16mm and 25mm diameters of rebars were investigated at finish rolling temperature of 915°C,917°C,918°C,920°C,922°C,923°C,keeping the % total deformations constant at 99%,while changing rolling strain rates to 7 x 10^3s -1 ,6 x 10 3 s -1 ,5 x 10 3 s -1 .

Mechanical tests were performed on the hotrolled samples at room temperature of 27°C on UPD 100s Universal Materials Testing Machine and PSW Pendulum Impact Testing Machine, respectively. The optimum finish rolling temperature,% total deformation and rolling strain rates were evaluated using the Response Surface Methodology. The yield strength, tensile strength and toughness were obtained from the mechanical test. Response surface methodology was used for the optimization of the yield strength, tensile strength and toughness of the hot rolled St60Mn steel. Actual values from the experimental data were used directly for the RSM experimental design. The behaviour of the yield strength ? y , tensile strength ? T ,and toughness E ImT, as obtained in the experimental data were modelled as functions of the finish rolling temperature and rolling strain rate using the Response Surface Methodology (RSM).The response surface methodology was obtained from the design expert software version 6.0.8.Response surface methodology usually aim at determining the optimum settings for the variables and to see how the variables perform over the whole experimental domain, including any interactions such as the simultaneous influence of the rolling process parameters on the properties of the hot rolled St60Mn steel. The finish rolling temperature and rolling strain rate were taken as two independent variables which determine the response of the yield strength ? y , tensile strength ? T ,and toughness E ImT , of the steel to the hot rolling process parameters. The experimental design and statistical analysis were performed according to the response surface analysis method using Design Expert 6.0.8 software. Historical data obtained from the experiments was employed to study the combined effect of the finish rolling temperature (x 1) and rolling strain rate (x 2).The dependent variables (y) measured were the yield strength ? y , tensile strength ? T and toughness E ImT , of the hot rolled St60Mn steel. These dependent variables were expressed individually as a function of the independent variables known as response function.

The cubic order three dimensional surface model was determined to describe the relationship between each of the properties y, and the two independent variables (finish rolling temperature;x 1 , and rolling strain rate;x 2).The model was able to account for the curvature of the response and the interaction of the independent variables in the response surface. The data point (y,x i ,x j) defines a curved surface in 3D space represented by the following polynomial (Karuppaiya et al.,2010;Lazic,2004;Man et al,2010). y =? 0 +? q j=1 ? j x j + ? q j= 1? jj x j 2 + ? q j=1 ? jj x j 3 + ? i< j?? ij x i x j + e

The parameters ? i are constant coefficients known as the regression coefficients. These coefficients measure the expected change in the response y per unit increase in x i when the x j is held constant and vice versa and are established by regression analysis in the RSM programme.

?? j x j is the main effect.?? jj x j 2 are the curvature,? i<j ?? ij x i x j is the interaction and e is the error.All the coefficients were obtained by the use of the Design Expert software package. The goodness of fit for each property model was confirmed by the R 2 values and the probability obtained from the analysis of variance (ANOVA).The optimum values of the rolling process parameters and the properties were obtained from the numerical analysis of the RSM package .Experiments were conducted at the optimal condition to validate the values obtained.

5 III.

6 Results and Discussion

a) Influence of finish rolling temperature on the mechanical properties at constant % total deformation of 99%, changing rolling strain rates to 7 x 10 3 s -1 ,6 x 10 3 s -1 and 5 x 10 3 s -1 .

The results obtained from the mechanical test experiments were used to describe the behavioural pattern of the yield strength ? y , tensile strength ? T and toughness E ImT , properties with the finish rolling temperature and rolling strain rates as shown in Figures 1.1,1.2 and 1.3.

The figures expose the influence of the finish rolling temperature and rolling strain rate on each of the properties. As shown in the figures, the tensile strength and yield strength decrease as the finish rolling temperature increases but increase as the rolling strain rates increase. But the toughness on the other hand, increases as the finish rolling temperature increases but decreases as the rolling strain rates increase. Year 2017 Table **??**.1 show the dependency of the yield strength, tensile strength and toughness on the finish rolling temperature for different rolling strain rates and % total deformations.

7 Global

The data in the tables were populated in the RSM actual-design value frame for the 18 observations obtained. The RSM capable of developing model fits for the data was used to develop the models describing the relationship of each of the properties with the hot-rolling parameters. Tables 3.2,3.3 and 3.4 below show the results of the model fit for the three mechanical properties under consideration as analysed using the RSM. The results suggest Quadratic order for the description of the mechanical properties relationship with the hot-rolling parameters as indicated in the tables. These are obtained by focusing on the model that maximizes the adjusted and predicted R-square values for each of the properties and the lowest level of uncertainty. The quadratic order compared to the other models has moderate standard deviation, high R 2 values and low predicted residual sum of squares for the three properties indicating that the quadratic model is the most suitable for describing each of the steel properties relationship with the process parameters.

The Analysis of Variance (ANOVA) for the response surface cubic models of the yield strength, tensile strength and toughness are shown in Tables below respectively with estimated values of the regression coefficients for 99%,98%,96% total deformation variables. The ANOVA is employed inorder to determine which of the variables in the rolling process parameters are significant in describing the behaviours of the mechanical properties.TheR 2 values were determined from the F-test.The significant parameters are shown in Tables below. Parameters with " Prob> F"-values less than 0.0001 are significant to the description of the properties relationship to the rolling process parameters.

Table3. 5: ANOVA for tensile strength relationship with finish rolling temperature at 99% deformation, changing rolling strain rates The F-values for the properties less than < 0.0001 implies that such models are significant. This means that there is only 0.01% chance that the model Fvalues as large as obtained could occur due to noise. The model terms with "prob>F" value < 0.0001 are considered to be significant and influence the responses considerably. Considering the finish rolling temperature relationship with the mechanical properties of hot rolled st60Mn steel at 99% deformation while changing rolling strain rates, the rolling parameter having the most significant influence on the properties was the finish rolling temperature (x 1) main effect with Fvalues of 4718.23,116.66 and 819.31,for tensile strength, yield strength and toughness respectively. This is followed by rolling strain rate (x 2) with F-values of 3704.18 ,212.41 and 7.96,both having "prob>F"< 0.0001.This implies that the finish rolling temperature has much more influence on the tensile strength and toughness with "prob>F" <0.0001,whereas the rolling strain rate has much more influence on the yield strength than the other two,with "prob>F"value <0.0001.The model terms having "prob>F"value >0.0001 indicates that the terms are not significant. Similar trends were observed for the other variables of 98%,96%, for the hot-rolled St60Mn steel. The determination coefficient R 2 values show a good response between the predicted values and the data for the properties at various variables of the parameters. This gives the confidence that the models describing the response of the properties are good fits of the model data. The adequate precision which measures the signal to noise ratios for the relationships describing the yield strength surface response, tensile strength surface response and the toughness surface response for all the variables of the rolling process parameters indicates adequate signals having been determined to be greater than 4.00 as shown in the Tables. It is required that this ratio greater than 4 is desirable. These models can therefore be used to navigate the design space for the three properties.

The satisfactory correlation between the data and the RSM predicted values is also evident as shown in the figures below, in which the plotted points are observed to be spaced out on the fit line as shown for the three properties respectively for 99%,98%,96% rolling process variables. It was observed that the residuals tend to be aligned with the normal distribution assumptions as defined by the straight lines. This implies that the errors are normally distributed. The predicted values for the properties as function of the process parameters could therefore be considered useful for getting information from the experiments.

The relative equations describing the response of each of the properties with the process parameters as obtained from the Response Surface Method are as Where x 1 is the finish rolling temperature (deg C) and x 2 is the rolling strain rate ($s^{-'}$).The contour of the responses as obtained in equations are calculated and was used to plot the surface response and the contour plots of the properties as shown below. The plots show the combined influence of the rolling process parameters on the yield strength, tensile strength and toughness of the hot rolled St60Mn steel samples for all the variables observed. The contour plots of the yield strength for all the variables observed showed similar curve shapes where yield strength decreases with increasing finish rolling temperature and increases with increasing rolling strain rates. Both rolling strain rate and finish rolling temperature shows a strong positive effect on the yield strength for all the variables observed. The characteristics of the contour plots for tensile strength are similar to that of the yield strength. The contour plots of the toughness for all the variables observed showed similar curve shapes where toughness increases with increasing finish rolling temperature and increases with decreasing rolling strain rates. The maximum achievable responses of the properties are well exposed on the contour plots. It is clear from the plots that the tensile strength and yield strength the hot rolled St60Mn steel decrease with increasing finish rolling temperature and increase with increasing rolling strain rates; whereas the toughness increases with increasing finish rolling temperature and increases with decreasing rolling strain rates. So these indicate that the maximum values of tensile and yield strength could be obtained at lower finish rolling temperature and higher rolling strain rates respectively, whearas the maximum values of toughness could be obtained at higher finish rolling temperature and lower rolling strain rates respectively; indicating considerable improvement of the properties at the respective parameters. The independent influence of the rolling process parameters is obtained on the surface plots. It was observed that the three parameters had equal influence on the properties at the variables observed. This influence is well exposed in the contour plots for the three properties. The improved yield strength is good for steel bars used in construction which tends to prevent failure of the steel when subjected to impact load. Therefore the yield and tensile strength should be maximized. The combined effect of the rolling process parameters is responsible for the curvatures of the plots. The implication is that the effect of the three parameters should be considered simultaneously for a global emergence of optimal process parameters for improved properties of the hot rolled St60Mn steel.

The effect of the finish rolling temperature,% total deformation and rolling strain rates on these properties could be optimized to avoid full recrystallization of the all the sample grains beyond the temperature range of

923°C.The criteria for optimization of the rolling process parameters were selected to maximize the yield strength, tensile strength and toughness for improved properties as required of the steel. The combined influence of the rolling process parameters on the simultaneous responses of the yield strength, tensile strength and toughness of the steel are presented in the Tables. The achievable optimal yield strength, tensile strength and toughness values were found as predicted in the tables with 95% confidence interval which ensures that the probability of the effectiveness of the optimization procedure is greater than 0.05.The corresponding parameters that yielded

8 Conclusion

The yield strength, tensile strength and toughness of hot-rolled St60Mn steel were evaluated when subjected to rolling process parameters towards obtaining the rolling process parameters that will be suitable for improving these properties of hot-rolled St60Mn steel to prevent the steel from the influence of poor mechanical properties which results in fracture failure when the steel is subjected to impact loads. The finish rolling temperature and rolling strain rate are found to influence these properties to a large extent as exposed in the Response Surface Analysis of the properties. The model developed by the RSM describing the experimental data shows that conclusion could be drawn from the model of the individual and combined interaction influence of the rolling parameters on the yield strength, tensile strength and toughness of the hot-rolled steel. The RSM was able to obtain the optimal values of the properties. The optimal yield strength ,tensile strength and toughness of the steel were obtained to be 470.13 MPa,701.63 MPa and 0.458042 joules/mm^2 respectively for the hot-rolled St60Mn steel.The RSM could be useful to obtain desired properties of hot-rolled St60Mn steel by controlling the rolling process parameters during hot-rolling. [1] [2] [3] [4]

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STEEL GRADE	CHEMICAL COMPOSITION %								
	C	Si	Mn	P	S	Cr	Ni	Cu	N
ST60Mn	0.41	0.24	1.12	0.021	0.008	0.02	0.03	0.03	0.010

a) Response Surface Modeling Technique

Figure 1: Table 2 . 1 :

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7 x $10^3 s^{-'}$
6 x $10^3 s^{-'}$

Figure 2: Table 3 . 1 :

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Figure 3: Table 3 . 2 :

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Model Summary Statistics for Yensile strength of hot rolled St60Mn steel at 99% deformation,changing rolli rates						
Source	Std.Dev.	R-Squared	Adujsted R-Squared	Predicted R-Squared	PRESS	
Linear	6.52	0.9364	0.9223	0.8979	614.21	
2FI	6.62	0.9417	0.9199	0.9044	575.00	
Quadratic	3.83	0.9854	0.9732	0.9367	380.79	Suggest d
Cubic	1.35	0.9988	0.9966	0.9131	522.66	Aliased

Figure 4: Table 3 . 3 :

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Source	Std.Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	6.227E-003	0.9031	0.8815	0.8250	6.299E-004	
2FI	6.440E-003	0.9078	0.8733	0.7365	9.484E-004	
Quadratic	1.852E-003	0.9943	0.9895	0.9536	1.670E-004	Suggested
Cubic	8.513E-004	0.9992	0.9978	0.9426	2.067E-004	Aliased

Figure 5: Table 3 . 4 :

	7000. 00 2 2		Yie ld s tre n g th			2 2
		4 6 9 .9 2 9				
	6500. 00		4 5 8 .7 9 3			
Rolling strain rate	6000. 00		4 3 6 .5 2 1 4 4 7 .6 5 7		4 2 5 .3 8 5	
B:						
	5500. 00					
Year 2017	5000. 00					2 2
54	915. 00	917. 00	919. 00	921. 00		923. 00
XVII Issue II Version I ( ) Volume Journal of Researches in Engineering Global © 2017 Global Journals Inc. (US)		A : F in is h ro llin g t e m p e ra t u re				

Figure 6: A

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Figure 7: Table 3 . 8 :

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