Optimization of Process Parameters by Reliability-Based Uncertainty Modeling of Cold Rolling Process

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ABSTRACT

Metal working processes can often be expressed in a reliability format. Information about present and anticipated reliabilities in metallurgical processes, in conjunction with decision models, provides a rational and powerful decision-making tool. In practice uncertainties arise in predicting service or lifetime loads in considering the variability in material properties, workmanship, process dimensions, environmental conditions, inspection test data, maintenance and so on. A wide range of materials with different elastic moduli, yield stresses, strain hardening and friction co-efficient constitute specific characteristics in a metal working process. Thus a metal working process may be defined as a collection of one or more related objects. Consequently, decisions related to rolling processes are based on uncertain or incomplete information. Finite element based process simulation can offer valuable guidelines on how the current process parameters should be modified to meet the requirements on the process and the product. This work represents a continued effort towards developing a sound methodology for modelling uncertainties in rolling process with reference to the reliability assessment. Based on the information obtained from the finite element simulation, investigations are conducted to assess the structural integrity of final product. The objective of this work is to use probabilistic methods to represent sources of uncertainty and to attain optimum set of points of rolling by iteration to achieve controlled microstructure of the finished product.

1.0 Introduction

Metallurgical processes can often be expressed in a reliability format. Information about present and anticipated reliabilities in metallurgical processes, in conjunction with decision models, provides a rational and powerful decision-making tool. In practice, uncertainties arise in predicting service or lifetime loads considering the variability in material properties, workmanship, element dimensions, environmental conditions, test data, maintenance and so on. Consequently, decisions related to metallurgical processes are based on uncertain or incomplete information [1, 2].

A metal forming process is characterized by various process parameters such as forming sequence, pass schedule, tool shapes, friction, temperature, forming speed, and material properties of the workpiece. Forming operations are carried out either by plastic deformation process or by machining/metal removal process. In plastic deformation the volume and the mass of the metal are conserved and the metal is displaced from one location to another. But in metal removal or machining process the material is removed to give it the required shape. The deformation zone is concerned with the distribution of stress, strain and overall pressure required to perform the operation. Obviously, the applied forces must develop yielding in the material but the stresses must not locally create fracture. The flow stress of the material will be a strong function of strain, strain rate and temperature [3, 4].

In view of the large tonnage of materials being processed by bulk metal working, any improvement in the processing techniques has a multiplying effect on overall productivity in manufacturing. The ultimate objective is to manufacture components with controlled microstructure and properties, without macro or microstructural defects, on a repeatable basis in a manufacturing environment [3, 4]. During the conceptual modeling phase, no mathematical equations are written, but the fundamental assumptions regarding possible events and metallurgical processes are made. The complexity of the model depends on the physical complexity of each phenomenon being considered. The model includes the complete specification of all partial differential equations, initial and auxiliary conditions, and boundary conditions for the processes. A probabilistic treatment of uncertainties generally requires that probability distributions can be established, either through data analysis or through objective judgments. Activities related to converting the mathematical models into a form that can be addressed through computational analysis. The first activity involves conversion of continuum mathematics form of the mathematical model into a discrete or numerical model. Algorithms and methods are prescribed in mathematically discrete form. Discrete values and discrete solutions exist with finite precision. Dependent variables, independent variables, space and time exists only at discrete points. Multiple solutions can also be required from the mathematical modeling phase if alternative models are to be investigated [5]. It contributes to the knowledge of the application of reliability based techniques for a metal forming process. Therefore, it is very appropriate to re-emphasize that the reliability based approach, as an analytical tool, greatly supplements the on-site work required to maintain the structural integrity. It also enhances the confidence level of the industry to place the product in service.

2.0 Uncertainty Modeling of Rolling Process

In uncertainty modeling, a performance function that describes the performance of the process in meeting the demand is defined as [6].

$$Z = g(X_1, X_2, X_3, \ldots X_n) \tag{1}$$

where X_1, X_2, X_3, ….. X_n are 'n' basic random variables of the process; 'g' is a function that describes the relationship between the basic random variables. The performance function in equation (1) is expressed such that failure of the process results in a negative sign for the function (i.e., $Z < 0$), survival of the process results in a positive sign for the function (i.e., $Z > 0$), and limit state for the process results in $Z = 0$. The approximate mean, μ_z, and standard deviation, σ_z, of 'Z' in equation (1) are estimated using the information on means, μ_{xi} and σ_{xi}, or the coefficient of variations (δ_{xi}) of the basic random variables, X_i. Expanding g(.) in equation (1) using Taylor's series expansion about the mean values of the basic random variables and truncating the series at the first-order terms, the first order approximate mean, the variance of Z are given by [6];

$$\mu_z \equiv g(\mu_{x1}\ \mu_{x2} \ldots, \mu_{xn}) \tag{2}$$

$$\sigma_z = \sum_{i}^{n} \left(\frac{dz}{dx_i}\right)_{\mu}^{2} \sigma_{xi}^{2} \tag{3}$$

Where the partial derivatives of 'Z' are evaluated at the mean values of the basic random variables. A measure of reliability can be defined by introducing a parameter 'β', called the reliability index as;

$$\beta = \frac{\mu_z}{\sigma_z} \tag{4}$$

'Z' having normal probability distribution, the reliability of the process is given by;

$$R_f = \varphi(\beta) \tag{5}$$

Where φ = cumulative probability distribution function of the standard normal variant and β is called the reliability index evaluating the reliability of the process [6].

Reliability has been modeled for four tandem mills of five stage cold rolling mill from industry. Softwares have been developed to evaluate the means, μ_{xi}, standard deviations σ_{xi} , and the coefficient of variations (δ_{xi}) of above random variables. Larke, developed the mean rate of deformation assuming the neutral plane to be co-incident with the exit plane for thin strip rolling [7]:

$$\dot{\varepsilon} = V \sqrt{\frac{2r}{D h_1}} \qquad r = \text{Relative reduction} = \frac{\Delta}{h_1} \qquad (6)$$

Where,

V = Rolling speed

h_1 = Entry thickness of workpiece

h_2 = Exist thickness of workpiece

$h\alpha$ = Thickness of workpiece at the neutral plane

D = Diameter of work roll

Δ = Draft = h_1 - h_2

Performance function 'Z' for the present work has been defined as follows [8]:

$$Z = \frac{\tau}{Y} - V \sqrt{r / R h_1} \qquad (7)$$

τ = Calculated average stress in roll bite from general purpose ABAQUS finite element package

Y = Yield stress of rolled material

Reliability index has been generated from a set of plant data from Industry for statistical analysis [Ref Tables 1 – 4]. Software tool has been developed to enable steel mill manufacturers and operators to optimum selection of process parameters in a high-speed mill for rolling of long steel products. Steady state solution of the deformation zone has been obtained by general purpose ABAQUS finite element package on nonlinear, transient dynamic analysis applying multilinear isotropic hardening proposition [Fig. 1, 2, 3].

Table 1. 1st Tandem Mill Data of Cold Rolling Mill from Industry

	Ref Material 'A'	Ref Material 'B'	Ref Material 'C'	Ref Material 'D'	Ref Material 'E'	Ref Material 'F'	Ref Material 'G'
Roll Dia 'D' mm	395.405	390.728	392.193	394.067	391.734	391.734	389.427
Incoming Strip Thickness	3.5	4	4	3	3.2	3	3.2
Reduction Given to Strip	33.2%	32.9%	26.8%	29.5%	22.5%	27.3%	28.1%
Stan Speed 'V' (Mtr per Min)	206	171	218	268	278	275	244
Rolling Load (Ton)	1248	1295	1192	1028	896	1178	1212

Table 2: 2nd Tandem Mill Data of Cold Rolling Mill from Industry

	Ref Material 'A'	Ref Material 'B'	Ref Material 'C'	Ref Material 'D'	Ref Material 'E'	Ref Material 'F'	Ref Material 'G'
Roll Dia 'D' mm	396.498	396.257	395.575	394.329	392.225	392.225	396.251
Incoming Strip Thickness	2.338	2.684	2.928	2.116	2.48	2.182	2.30
Reduction Given to Strip	37.6%	37.9%	29.4%	32.9%	27.8%	27.8%	29.8%
Stan Speed 'V' (Mtr per Min)	324	278	316	413	392	393	356
Rolling Load (Ton)	1400	1441	1338	1131	1057	1348	1380

Table 3: 3rd Tandem Mill Data of Cold Rolling Mill from

	Ref Material 'A'	Ref Material 'B'	Ref Material 'C'	Ref Material 'D'	Ref Material 'E'	Ref Material 'F'	Ref Material 'G'
Roll Dia 'D' mm	413.683	409.688	396.962	411.77	413.218	413.218	395.849
Incoming Strip Thickness	1.458	1.666	2.068	1.42	1.79	1.574	1.616
Reduction Given to Strip	32%	33.1%	27.5%	31.2%	24.3%	28.5%	29.1%
Stan Speed 'V' (Mtr per Min)	488	415	436	599	517	549	501
Rolling Load (Ton)	1117	1188	1124	941	896	1176	1129

Table 4 : 4th Tandem Mill Data of Cold Rolling Mill from Industry

	Ref Material 'A'	Ref Material 'B'	Ref Material 'C'	Ref Material 'D'	Ref Material 'E'	Ref Material 'F'	Ref Material 'G'
Roll Dia 'D' mm	421.233	407.055	426.507	422.976	422.244	422.244	405.674
Incoming Strip Thickness	0.992	1.116	1.498	0.976	1.356	1.126	1.146
Reduction Given to Strip	29.6%	31.6%	27.8%	29.6%	21.3%	25.2%	26.4%
Stan Speed 'V' (Mtr per Min)	712	603	616	846	659	740	693
Rolling Load (Ton)	965	979	1035	856	817	1040	1036

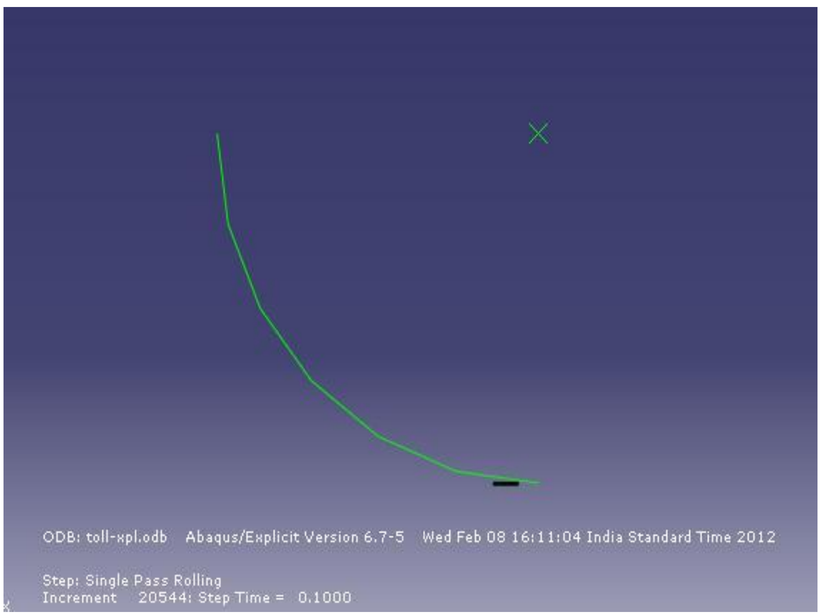

Fig 1: Roll workpiece contact at the onset of rolling from all purpose software ABAQUS

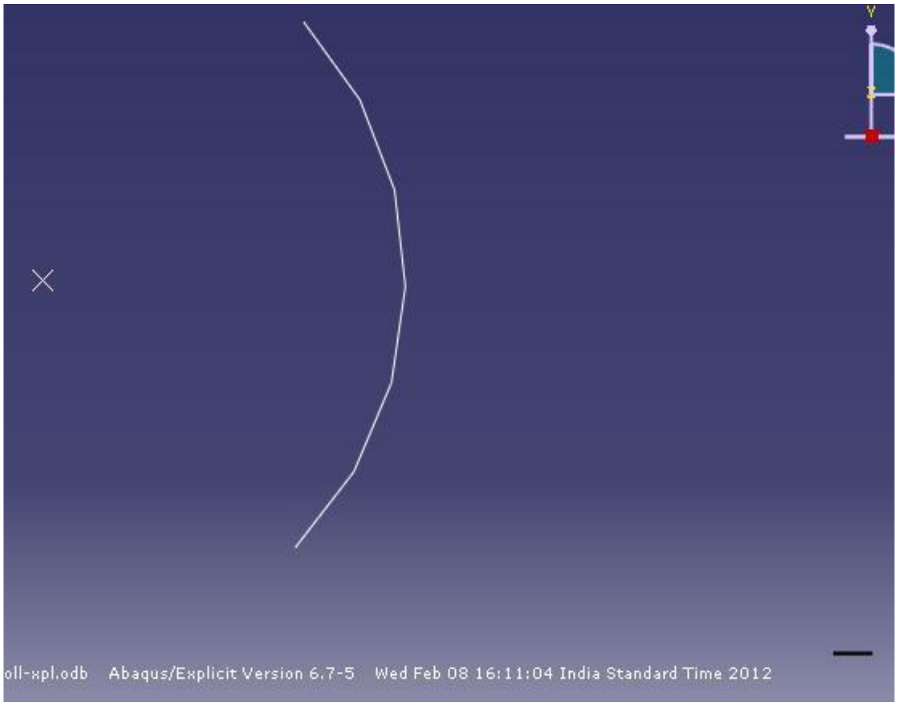

Fig 2: Completion of single pass rolling from all purpose software ABAQUS

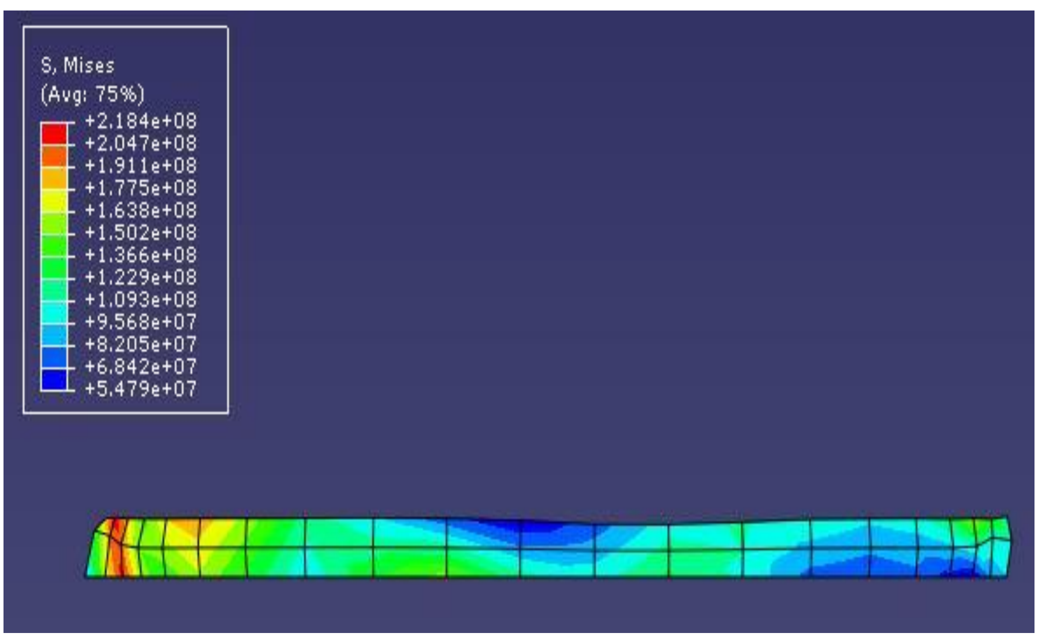

Fig 3: Finite element model for Misse's stress in typical roll bite from all purpose software ABAQUS

3.0 Interpretation of Present Work

Parameters affecting resistance to deformation in rolling are: (i) material chemical composition (ii) material metallurgical characteristics, (iii) material temperature, (iv) geometry of deformation zone, (v) external friction in the deformation zone, (vi) material work hardening prior to the rolling pass under consideration and (vii) strain rate deformation.

In this work simplified formula by Tselikov has been used for modeling resistance to deformation and the above said parameters [8] :

$$K_W = \frac{1.15Y(2-r)}{r\delta}\left[\left(\frac{1}{1-r}\right)^{\delta/2} - 1\right] \quad (8)$$

Where, $\delta = \frac{2\mu L}{\Delta}$ $\quad L = \sqrt{R\Delta - \Delta^2/4}$ (9)

From cumulative distribution function of standard normal [Fig. 4], the reliabilities are defined as 93.2%, 92.36%, 91.46% and 90.82% respectively for 1^{st}, 2^{nd} , 3^{rd} and 4^{th} tandem mills respectively of operating mills. The outcome of the new process [Fig.5] clearly indicates drastic reduction in the resistance to deformation with increase in reliability indexes for respective tandem mills. There is wide range of scope for optimization as marked in the graph for better operation by computer control of the cold mills [Fig.5]. This needs large scale development of soft ware coding for process simulation. The outcome provides an introduction to the area of reliability assessment as estimation of the likelihood of unacceptable performances and assurance of some level of reliability.

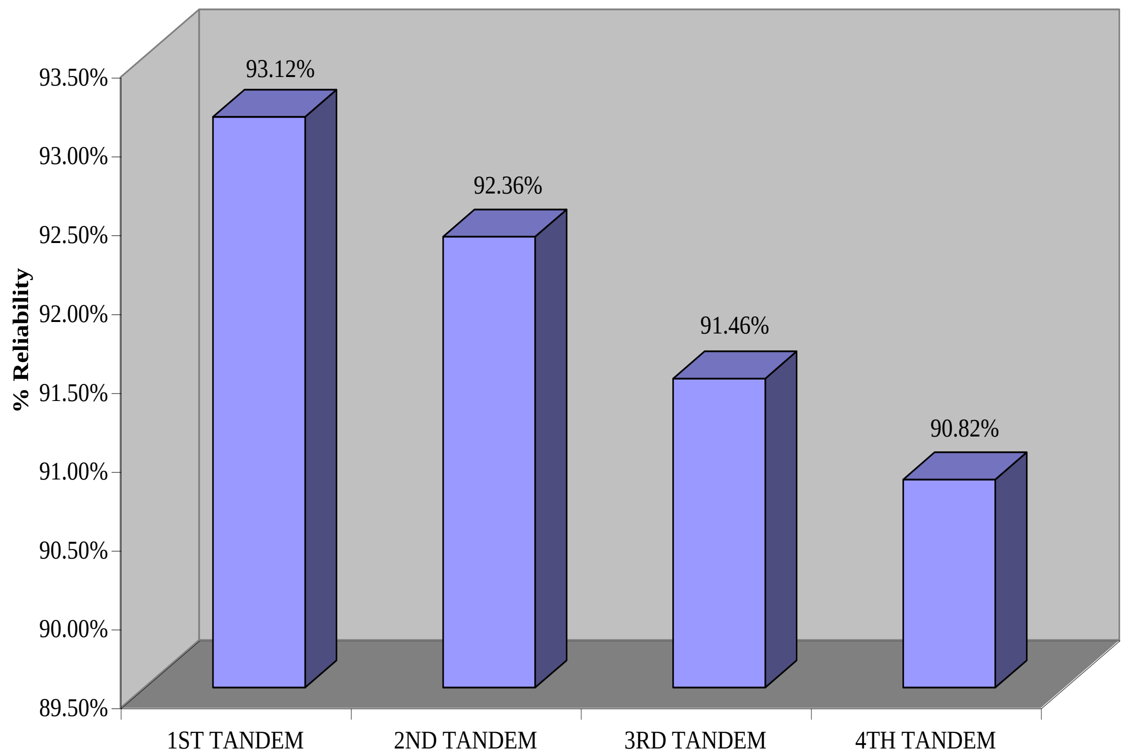

Fig 4: Reliability Measure for tandem mills from software output of industrial input data

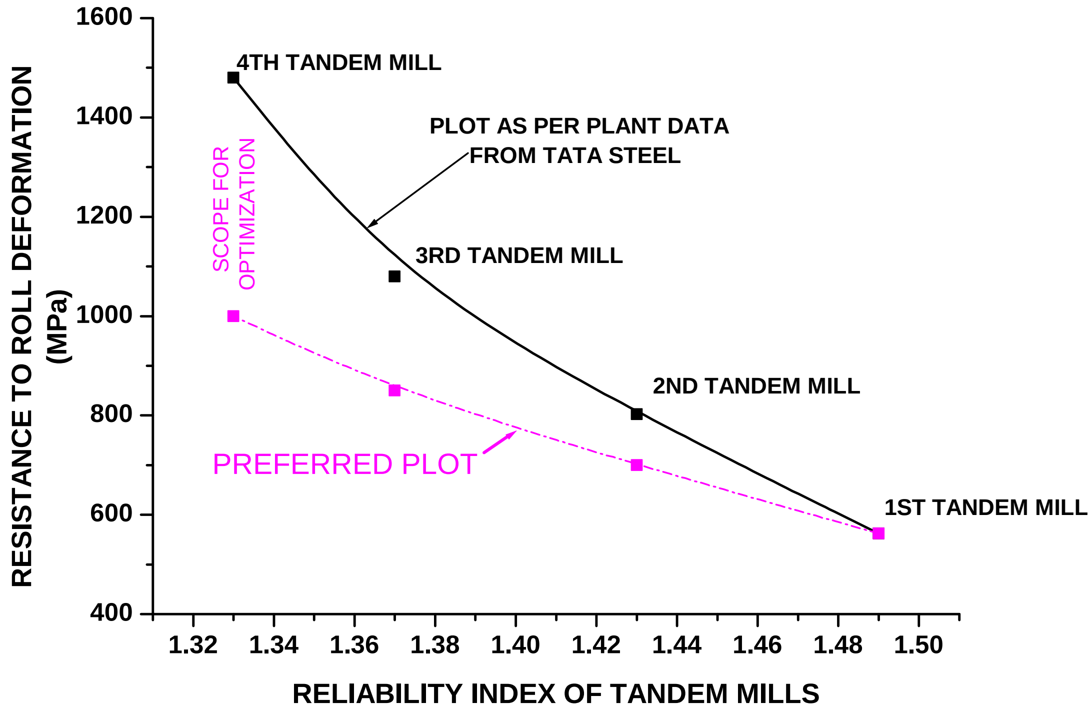

Fig 5: Plot of resistance to deformation and reliability index from software output of industrial input data

4. Conclusion

Interpretation of performance parameter with reference to resistance to deformation of rolling process has been explained and scope of optimization of process parameters to minimize the resistance to deformation has been defined. Performance parameters have been identified based on statistical data of operating parameters for reliability measurement of uncertainties of roll operation. Random mill operating data have been collected from industry for simulation of newly defined optimization process. Solution of the deformation zone to obtain stress distribution in the transition zone of the workpiece in rolling, has been carried out by all purpose software ABAQUS based on nonlinear, transient dynamic analysis applying mill operation data. Software has been developed for the generation of Reliability Index by First Order Reliability Method and resistance to deformation applying FORTRAN 90.

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