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IN-SITU STRAIN EVALUATION DURING COLD ROLLING OF AL 1100H14

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ABSTRACT

Cold rolling is used to produce metal sheets of superior surface quality and close tolerances. Till now, behavior of metal under application of the load has been understood by a uniaxial tensile test. However, the behavior of metal under actual contact conditions may be more complex and cannot be compared with data obtained in tensile tests. In this paper, attempts have been made to evaluate *in-situ* strain under simulated contact conditions to predict allowable reduction without cracking. Experiments were performed on specially designed and developed laboratory type rolling mill. The authors tried to evaluate work hardening index and its coefficient for Al 1100H14 under actual contact conditions. Further experiments based on the Taguchi's technique in order to evaluate the effect of rolling speed, percentage reduction, entry thickness and contact conditions on linear strain were carried out and ranking of parameters was done. This approach will be helpful for manufacturers in order to understand its limiting behavior to straining for newer materials.

***Keywords**: Cold rolling, Strains, Work hardening index and Rolling load*

1. Introduction

Cold rolling is used to produce metal sheets of superior surface quality and close tolerances. Around 50 percent of aluminum production is in the form of sheets and strips worldwide. Today, cold rolling mills around the globe are continuously looking for ways to increase their productivity, save energy, minimization of production cost and superior product quality. Numerous investigations have been carried out for the analysis of rolling process theoretically as well as experimentally [1, 5, 7]. Behavior of the metal subjected to load has been understood conventionally by uni-axial tensile test. However, the behavior of metal under actual contact conditions may be more complex and cannot be comparable with data obtained in tensile tests. Most of the nonferrous metals like aluminum do not show sudden bend or kink in their stress-strain curve, instead gradual transition from elastic to plastic state was observed [9]. Also it depends on many parameters such as type of process, direction and amount of load applied, material characteristics, frictional characteristics of contacting surfaces, surface integrities, lubrication mechanism etc. Hardness of a metal is also an indirect measure of strain hardening and it affects the tribo-mechanical properties of forming operations. Up till now, investigations have been carried out to determine tribological effects[2, 6, 10], frictional characteristics [3], roll separating force [6] in cold rolling and other similar metal forming process [4,8]. Chaohuiet. al. [7] investigated the mechanism of formation of micro-cracks in aluminum sheet during cold rolling.

Formability study by etching circle grid pattern to find-out critical areas of failures in deep drawing processes have been investigated and using circle grid pattern and measuring the strains. Forming limit diagrams were plotted to predict the workability of metal sheets. Hardly any work related with *in-situ* strain measurement while cold rolling of aluminium has been reported in literature. The objectives of present study are to determine the effect of cold rolling parameters on strains under actual contact conditions of aluminum. Attempts have been made to study the effect of reduction, speed, entry thickness, interface between roll and strip (i.e. wet or dry) on strain. It is worthwhile to study the effectiveness of experimental data for the sake of understanding behavior of metal under actual contact conditions which could act as useful information to the manufacturers. Also the approach will be helpful for manufacturers in order to establish

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cold rolling technology for newly developed non-ferrous material and its alloy.

2. Experimental Set-up

The experiments were carried out on a specially designed and developed laboratory type two-high cold rolling mill, with roll diameter of 106 mm and barrel width 152.4 mm. The mill is powered by 5.5 HP, 1440 rpm, AC motor, with variable frequency drive (VFD). Speed reduction is achieved through a reduction gear box and the output speed (roll speed) varies between 5 to 60 rpm. The rolls are made up of 9Cr tool steel material, hardened to 50 Rc and finished around 0.3 µm. Both the rolls are driven by a heavy duty pinion stand. Rolls are independently adjusted. The mill can withstand maximum roll separating force of 250 KN. The mill has a proximity sensor for online measurement and display of roll speed. Fig. 1shows a schematic of laboratory type two high rolling mill.

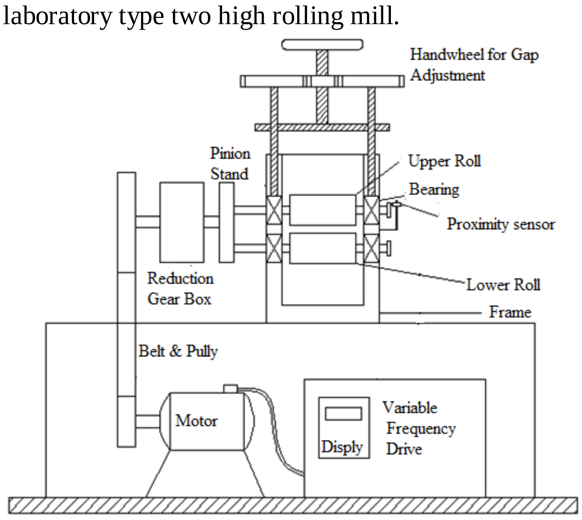

Fig. 1 Schematic of laboratory type rolling mill

3. Material and Method

The material selected for the study is Aluminum 1100-H14, a common commercial grade aluminum where intrinsic formability and corrosion resistance is needed. Al 1100-H14 is semi hard to obtain the desired strength level without any subsequent thermal treatment. A strip size 25mm wide, 300 mm long in two thicknesses as 0.9 mm and 1.4 mm have been prepared. The centerline average roughness of the surfaces of strip is ~0.4 µm. Table 1 depicts the mechanical properties and Table 2 gives chemical composition of Aluminum 1100H14.

Table 1 Mechanical Properties of Al 1100H14

Material	Al 1100 H14
Tensile Yield Strength	115MPa
Ultimate Tensile Strength	125MPa
Brinell Hardness	32 HB
Density	2.71g/cm^3
Modulus of Elasticity	69GPa

Table 2 Chemical composition of Al 1100 H14

Al	Si+ Fe	Cu	Zn	Mn	Residual
99 %	1%	0.2 %	0.1 %	0.05 %	0.15 %

The rolls and the specimens were cleaned with acetone, before and after every pass. Sheets are etched electrochemically to imprint a circle (of diameter d_i) on the surface of the sheet as shown in Fig. 2. A sheet of initial thickness h_{entry} is allowed to pass for a set amount of reduction through the two rotating rolls to a thickness (h_{exit}). The previously inscribed circle diameter is now deformed into ellipse after reduction in thickness and major circle diameter (d_f) *was measured*. The deformation in lateral direction is found to be negligible. The strain, e_1, in longitudinal direction is calculated by using the equation 1. It is assumed spread and slip in the process are negligible.

$$e_1 = \frac{(d_i - d_f)}{d_i} \quad (1)$$

An empirical equation[5] for determination of rolling load more precisely is

$$RL = bm\sqrt{R.\Delta h}\,\sigma_0{'} .\left[1 + \frac{1.6\,\mu.\sqrt{R.\Delta h} - 1.2\,\Delta h}{h_{entry}+h_{exit}}\right] \quad (2)$$

Where, RL is rolling Load, *bm* is a mean width of strip, Δh is reduction, R Roll radius, h_{entry} *and* h_{exit} are entry and exit thickness of sheet respectively.

$$\sigma_0{'} = \frac{2}{\sqrt{3}}\sigma_0,$$

where, σ_0 is mean stress in tension (for this material assumed a standard value of 115 Mpa).

In the above equation µ is a coefficient of friction between strip and roll surface. Though friction in roll gap may not be constant throughout, attempts have been made by [2-5] to evaluate friction coefficient practically for Al 1100 H14 and found that it varies in roll gap between 0.12 to 0.15 for the variable amount of reduction. Hence, friction coefficient for dry rolling was assumed to be 0.13.

The contact area between the strip and roll surface while rolling at an instant (refer Fig. 2)

$$\text{Contact area} = \sqrt{R.\Delta h}\,.\,bm \quad (3)$$

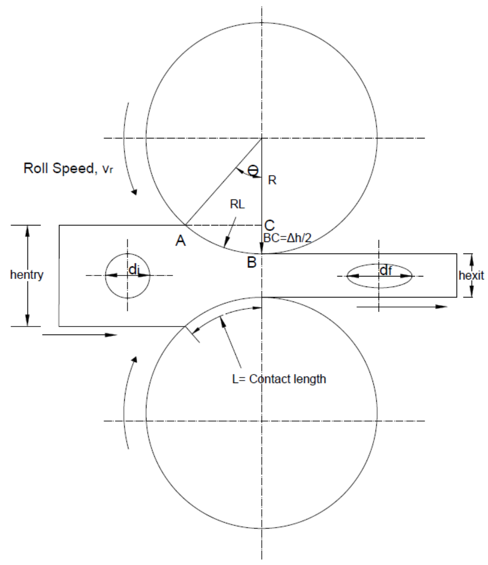

Fig. 2 Cold rolling Terminology

4. Results and Discussion

4.1 Determination of In-situ Work Hardening Index

Primary experiments were performed to study the effect of reduction, speed, entry thickness and contact conditions on the strain. Other parameters like material property variation, friction, type and viscosity of lube oil etc., which would have some effect on reduction have not taken into consideration for the sake of simplicity. A circle of diameter 12mm is inscribed on the surface of strip having 25 mm width and is passed for set amount of reduction. After reduction, etched circle gets deformed and converted into ellipse. The major and minor diameters of the ellipse were directly measured by a transparent scale (Maylors Tape) and strain was calculated using equation 1. Experimental results are depicted in Fig. 3.

In order to evaluate the rolling load and cumulative strain, the same strip was continuously passed for further higher amount of reduction till it gets crack. Strains were measured after each pass. Based on the measured strains and reduction the rolling load and stress were evaluated using Eq. 2 and 3. The load extension plot (Fig. 4) and Stress-strain curve (Fig. 5) were plotted. The equation of the curve $\sigma = 243.7\epsilon^{0.226}$ depicts work hardening coefficient K is 243.7 and work hardening index 0.226 for Al 1100 H14 are evaluated.

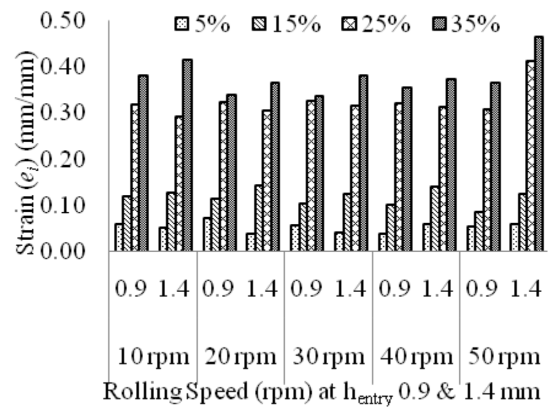

Fig. 3 Effect of rolling speed (rpm), reduction and entry thickness (h_{entry} = 0.9 & 1.4)

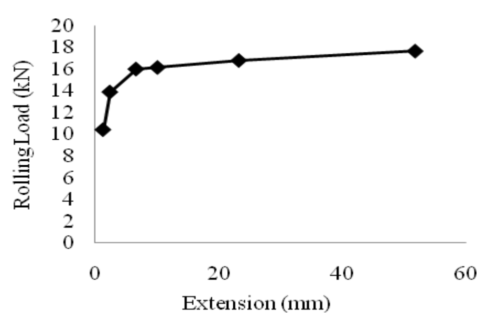

Fig. 4 In-situ Rolling Load Vs Extension curve for Al 1100 H14

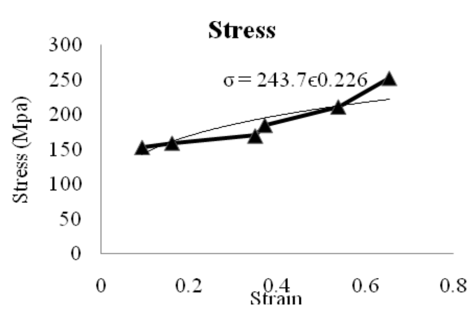

Fig. 5 Stress-Strain curve for Al 1100 H14 under actual contact conditions

4.2 Experimental Design

Further experiments were planned using Taguchi's design of experiments [Orthogonal Array of L_{16}]. In Table 3 the factors studied and the corresponding levels are indicated. L_{16} orthogonal array was chosen to evaluate effect of percentage reduction, entry thickness and roll speed and contact conditions. In order to produce wet condition, commercially used cold rolling oil was applied by brush on both sides of the strip. The response measured was longitudinal strain.

Table 3: Different Level of Variables

Factors	Levels I	Levels II	Unit
% Reduction (R)	15	35	--
Entry Thickness (h_{entry})	0.9	1.4	mm
Roll Speed (V)	20	40	rpm
Contact Condition	Dry	Wet	--

4.3 Data Analysis and S/N Ratios

Authors performed Taguchi [L_{16}] test to find out the significance parameter affecting strain for the said material. The signal to noise ratio (S/N) expresses the scatter around a target value. Taguchi's loss function can be expressed in terms of Mean Square Deviation (MSD), and thus S/N ratios as.

$$S/N = -10 \log (MSD) \quad (4)$$

Where MSD = Mean Square Deviation.

For larger is better:

$$MSD = \left(\frac{1}{Y_1^2} + \frac{1}{Y_2^2} + \frac{1}{Y_3^2} + \cdots\cdots\cdots\right)/n \quad (5)$$

Where n is the number of observations and y is the observed data.

Table 4 Experimental Results

(%) Red	h_{entry} (mm)	Speed (V)	Contact Cond.	Strain 1	Strain 2	S/N ratios
15	0.9	20	Dry	0.147	0.143	-16.77
15	0.9	20	Wet	0.267	0.261	-11.56
15	0.9	40	Dry	0.133	0.141	-17.27
15	0.9	40	Wet	0.242	0.249	-12.20
15	1.4	20	Dry	0.150	0.148	-16.53
15	1.4	20	Wet	0.277	0.272	-11.23
15	1.4	40	Dry	0.147	0.152	-16.51
15	1.4	40	Wet	0.256	0.259	-11.78
35	0.9	20	Dry	0.463	0.470	-6.62
35	0.9	20	Wet	0.573	0.580	-4.78
35	0.9	40	Dry	0.456	0.469	-6.70
35	0.9	40	Wet	0.535	0.537	-5.41
35	1.4	20	Dry	0.510	0.511	-5.84
35	1.4	20	Wet	0.565	0.564	-4.96
35	1.4	40	Dry	0.489	0.494	-6.16
35	1.4	40	Wet	0.594	0.599	-4.48

The tests were replicated to allow the analysis of variance of the results. Using MINITAB-17, Taguchi Design Software, S/N ratios were calculated (Table 4).

Ranking of parameters are done and shown in Table 5. Here, Delta denotes proportionate change in S/N ratio. Analysis of variance is depicted in Table 6.

Table 5 Response Table for S/N ratios

Level	Percent Red. (R)	Entry Thickness (h_{entry})	Roll Speed (V)	Contact Condition
1	-14.23	-10.16	-09.79	-11.55
2	-05.62	-09.69	-10.06	-8.30
Delta	08.61	00.47	00.27	3.25
Rank	1	3	4	2

Table 6 Analysis of Variance

Factors	DOF	Sum of Squares (s)	Variance (v)	Percent Cont. (P)
Percentage Reduction	1	296.67	296.67	83.637
Entry Thickness	1	00.910	00.91	0.111
Roll Speed	1	00.310	00.31	0.087
Contact Conditions	1	42.210	42.21	11.77
Error	27	13.989	0.52	3.95
Total	31	354.089		

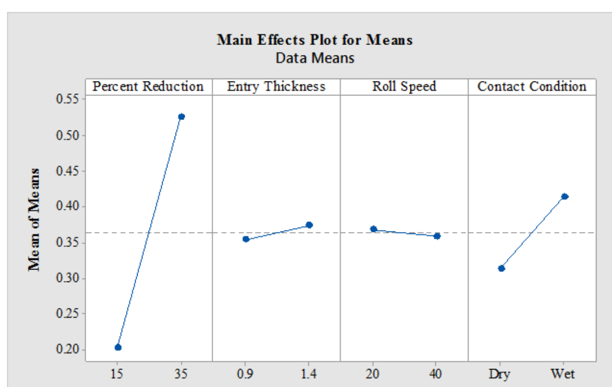

Fig. 6 The Main effect plot for Means

Analysis of variance reveals that, percentage reduction has dominant effect on strain; however contact conditions are also important to determine strains in cold rolling. Entry thickness and roll speed have shown very little effect on strain in selected range, however to get magnified effect, experiments could be conducted with wider range on actual rolling mill since laboratory type rolling mill have its own limitations. The main effect plot for data means (Fig. 6) and for S/N ratios (fig. 7) are plotted for various parameters.

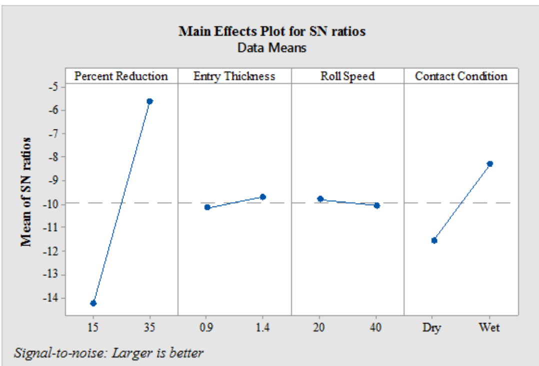

Fig. 7 The main effect plot for SN ratios

5. Conclusion

Authors have demonstrated a simple and effective method of *in*-situ measurement of strain in cold rolling of Al 1100 H14. Taguchi's analysis method has enabled to analyze successfully the effect of selected test parameters. Ranking of the parameters has been done and it was found that percentage reduction is the most dominating parameter in determination of strain followed by contact conditions (dry or wet) that means lubricant plays very important role to allow higher strains; however roll speed and entry thickness have marginal effect on strain in selected range.

A typical stress-strain curve depicting actual rolling could be plotted. Results show that, for material Al 1100 H14, $\sigma = 243.7\ \epsilon^{0.226}$, where strain hardening index is 0.226. This methodology will be helpful for manufacturers in order to establish cold rolling technology for newly developed non-ferrous material and its alloy to understand its limiting behavior to straining.

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