The Zener-Hollomon Parameter Characteristics in Hot Rolling of AISI 316 using the Reverse Sandwich Model.

O.J. Alamu, Ph.D.[1], S.O. Giwa, M.Sc.[2], M.A. Sulaiman, M.Sc.[2], C.C. Enweremadu, Ph.D.[3], and I.A. Lateef, B.Tech.[4]

[1]Department of Mechanical Engineering, University of Agriculture, PMB2240, Abeokuta, Nigeria
[2]Olabisi Onabanjo University (Ibogun Campus), PMB 5026, Ifo Post Office, Nigeria
[3]Ladoke Akintola University of Technology, PMB 4000, Ogbomoso, Nigeria.
[4]Department of Mechanical Engineering, Osun State College of Technology, Esa-Oke, Nigeria.

E-mail: tolasum@yahoo.com ; baale_i@yahoo.com

ABSTRACT

For hot rolling of AISI Type 316 Stainless Steel at low strain rates, temperature distribution in the through-thickness of the slab are now predicted with better accuracy using the Reverse Sandwich Model (RSM) compared with results from the Bland and Ford's theory or Sims' theory. Recent studies have examined the sensitivity analysis of roll bite parameters on the temperature distribution in this material during hot rolling. However, predictions of the Zener-Hollomon Parameter distribution in the through-thickness of AISI 316 slab, using the RSM, has not been sufficiently explored. In this work, the temperature compensated empirical equation due to Zener and Hollomon was integrated into the RSM. This was then simulated using FORTRAN 77. The developed program was validated with experimental data from 2 Hi Reversing Rolling Mill. Results obtained, revealed a symmetrical decrease in the Zener-Hollomon parameter values from the rolling surfaces towards the core of the material. At zones close to the roll contact, lower gradients were observed in the Zener-Hollomon parameter. The computer simulation showed good agreement with experimental measurement.

(Keywords: stainless steel production, reverse sandwich, RSM, hot rolling, deformation, strain rate)

INTRODUCTION

Disparity between experimental values and theoretical predictions of roll bite parameters such as friction, stress, roll force, and torque during hot rolling of metals have been reported by numerous authors *[1, 2, 3, 4]*. Chikara and Johnson *[4]* observed a disagreement in the hot rolling of relatively heavy sections, where the initial width / thickness ratio is less than six (e.g. ingot to billet). This was attributed to the simplifying assumption of plane strain usually made in rolling theories, which permits slip-line field approach to be employed *[5]*.

This assumption is reasonable for cold rolling of thin strips or when hot rolling strips with width / thickness ratio greater than six *[6]*. Even for hot rolling at such thinner gauges, deviations have been reported in experimental values and theoretical predictions *[7]*.

For hot rolling of AISI Type 316 Stainless Steel at low strain rates ($0.01s^{-1}$ - $1.55s^{-1}$), compatible with the speed of continuous casters for in-line rolling, experience has shown that theoretical predictions of rolling load and torque using simple rolling theories and simple rolling temperature based on the mean entry temperature became unreliable *[1, 8]*.

Using a modified Leduc's Program based on Sim's theory, with the mean entry temperature as the mean rolling temperature, Ayedun *[1, 8*] reported 15-25% excess load and torque compared with experimental values. He concluded that the underestimation of these parameters was a result of precipitation hardening as well as temperature gradients leading to a higher strength of the surface layer of the slab compared with the bulk (called Roll Chilling or Reverse Sandwich Effect) *[1, 8]*. This was further reported to be more pronounced at low strain rates *[9]*.

Roll Chilling, in other words, is a reversed situation to sandwich rolling (Figure 1), where hard metal strips are rolled between layers of softer metals *[7, 10, 11]*.

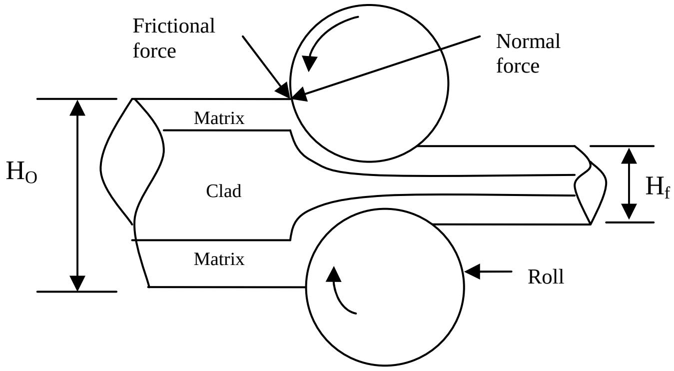

Figure 1: ^{1}Sandwich / ^{2}Reverse Sandwich Rolling Process.
(^{1}soft matrix, hard clad; ^{2}hard matrix, soft clad)

To account for the observed deviation of theoretical predictions from experimental / industrial measurements of the hot rolling parameters due to the temperature gradients, the Reverse Sandwich Model (RSM) was proposed *[1, 8, 12]* for AISI Type 316 Stainless Steel. Integration of this model into hot rolling theory of Bland and Ford *[13]* yielded better agreement between measured and predicted values of hot rolling parameters such as load, torque, yield stresses and temperature. Computer simulation of this model aided a through-thickness prediction of temperatures in the slab during hot rolling *[14]*. Besides, in rolling processes generally, it is vital to know the temperature distribution within the slab.

Reports exist in the literature *[15]* that temperature is the dominant parameter controlling the kinetics of metallurgical transformations and the flow stress of the rolled metal. Computer simulation of the RSM further made possible sensitivity analysis of roll bite parameters on temperature gradient during the hot rolling of this material at low strain rates *[16, 17]*

However, only limited works have appeared in literature on Simulation of Reverse Sandwich Model with particular attention to the Zener-Holloman parameter. The Zener-Hollomon parameter is uniquely related to stresses, and gives an indication of deformation in a material. Lower values of the Zener-Hollomon parameter has been confirmed as an indication of greater deformation in the material during rolling process *[1, 8]*. Using the Reverse Sandwich Model, a computer simulation of the Zener-Hollomon parameter is carried out with a view to analyzing the Zener-Hollomon parameter values corresponding to temperature distribution in AISI type 316 Stainless Steel during hot rolling.

MATERIALS AND METHODS

The Reverse Sandwich Model predicts the rolling reduction, rolling temperatures, and temperature distribution along the through thickness of AISI type 316 Stainless Steel. Detailed theoretical analysis of the model are available elsewhere *[9, 12, 13, 14]*, only portions relevant to this study are hereby presented.

CALCULATION OF REDUCTION AND DEFORMED ROLL RADIUS

By the usual notations:

$$\delta = H_f - H_o \qquad \textbf{(1)}$$

where; δ = rolling reduction, (mm), H_f = final specimen thickness, (mm), and H_o = initial specimen thickness, (mm).

Percentage rolling reduction is therefore given as:

$$r = \frac{H_f - H_o}{H_o} X100\% \qquad \textbf{(2)}$$

Sims' hot flat rolling theory assumes a circular arc of contact, which is flattened in accordance with Hitchcok's formula. Thus,

$$R` = R_o\left(1 + \frac{C.P}{\delta.W}\right) \qquad \textbf{(3)}$$

where, R' = radius of curvature of the elastically deformed roll, (mm), Ro = un-deformed roll radius, (mm), P = vertical roll pressure, (N/mm^2) W = width of the material, (mm), C = constant, and,

$$C = 8\frac{\left(1 - \nu^2\right)}{\pi E} \qquad \textbf{(4)}$$

This equals 0.0223 mm^2 /kN for steel rolls and 0.0247 mm^2 /kN for chilled C.I. rolls; also, P =132KN/ mm^2 *[1, 18].*

HEGHT OF MATERIAL ALONG THICKNESS

The specimen is partitioned into 17 zones (Figure 2). This portion of the model has been described elsewhere *[12, 13, 14]*.

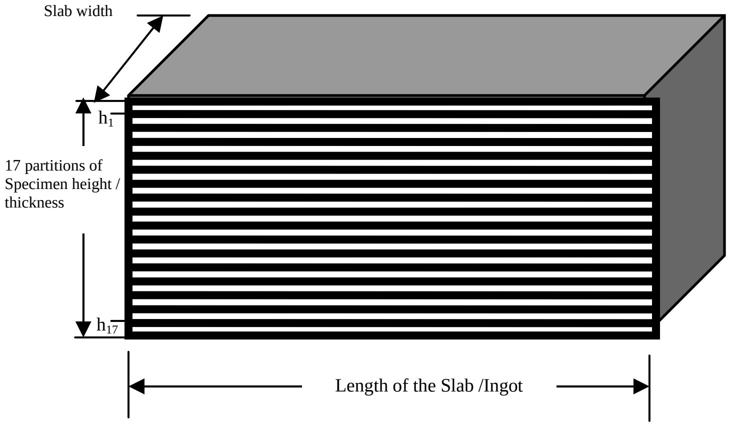

Figure 2: Illustration of the Rolling Specimen Partitioned into 17 Zones.

ROLLING TEMPERATURES

The model's prediction of rolling temperature follows Equation (5) to (8).

$$T_S = \frac{T_f}{K} \qquad \textbf{(5)}$$

$$T_M = 0.5(T_F + T_s) \qquad \textbf{(6)}$$

$$Tc = \tfrac{1}{2}(T_M - T_F) \qquad \textbf{(7)}$$

$$\left.\begin{array}{ll} \text{For } 1 \le n \le 4 \text{ and } 15 \ge n \ge 12, & \\ T_{n+1} = T_n + 0.2\,T_{DIST} & \text{(a)} \\ & \\ \text{For } 8 < n < 9, & \\ T_{n+1} = T_{DIST} & \text{(b)} \\ & \\ \text{For } 5 \le n \le 7 \text{ and } 11 \ge n \ge 9, & \\ T_{n+1} = T_n + 0.04\,T_{DIST} & \text{(c)} \end{array}\right\} \textbf{(8)}$$

where: T_F = furnace temperature, (C), T = the mean rolling temperature, (C)

Ts = exit surface temperature, (C), and K = reverse sandwich model constant.

REVERSE SANDWICH ROLLING SPEED

The rolling speed is related to the reverse sandwich model constant as follows *[12]*:

$$\left.\begin{array}{ll} \text{For } 9 \le V \le 10, K = 1.59 & \text{(a)} \\ 10 \le V \le 45, \ K = 1.40 & \text{(b)} \\ 45 \le V \le 100, \ K = 1.19 & \text{(c)} \\ 100 \le V \le 180, \ K = 1.16 & \text{(d)} \end{array}\right\} \textbf{(9)}$$

where V = Peripheral velocity of rolls (mms^{-1}).

MEAN STRAIN RATE

The approximate empirical equation of Farag and Sellars, *[19]* was used in the model for determination of mean strain rate thus:

$$\varepsilon = \frac{1.08V}{R`\delta}\left(\frac{\left(\delta^2\right)^{(0.25)}}{h_1 h_2}\right)\left[\ln\frac{h_o}{h_f}\right]^{0.45} \qquad \textbf{(10)}$$

where: δ = reduction (mm) and V = peripheral velocity of rolls (mms^{-1}).

ZENER-HOLLOMON PARAMETER ALONG MATERIAL'S THICKNESS

The Zener-Hollomon parameter was determined for each of the seventeen (17) zones along thickness (Z_1-Z_{17}) using the proposition of Zener and Hollomon, *[1, 8]* written as:

$$\sigma = f\left(\varepsilon.\exp\left(\frac{Q}{RT}\right)\right) = f(Z) \qquad \textbf{(11)}$$

where,

R = universal constant, (J /mol K)
T = absolute temperature, (C)
Z = Zener-Hollomon parameter

Q is the energy that must be supplied by the thermal fluctuation to overcome obstacles such as dislocations.

The Z-values are uniquely related to the stress, and, hence the deformation of the material. For

AISI 316 Stainless Steel under the prevailing rolling condition, Q = 460kJ / mol *[1, 8]*.

MODEL SIMULATION AND VALIDATION

Computation of strain rate and the Zener-Hollomon Parameter was integrated into the Reverse Sandwich Model. This was subsequently developed into computer codes written in FORTRAN 77.

The program computes both the temperature and Zener-Hollomon parameter values corresponding to each of the 17 zones, to which the material was partitioned. The program also computes the mean rolling temperature for each rolling schedule. Validation of the computer codes was carried out using five different specimens of AISI Type 316 SS with predetermined hot rolling experimental data. The specimens were hot rolled at varying reductions, widths, furnace temperatures, and rolling speeds on 2 High Reversing Rolling Mills according to the extracted schedule (Table I) *[1, 8]*.

Table 1: Specimen Schedule for Program Validation.

Specimen No. S/N		Roll Radius (mm)	Furnace Temp. (C)	Rolling Speed (mms^{-1})	Initial Height (mm)	Final Height (mm)	Width (mm)
1	P55	139.70	1118.0	25.40	16.18	15.21	74.93
2	P48	139.70	1109.0	23.10	15.88	13.50	75.00
3	P50	139.70	1113.0	20.20	16.08	12.72	75.00
4	P59	139.70	1134.0	18.60	12.10	10.80	75.10
5	P61	139.70	1124.0	17.30	7.83	7.02	75.20

For validation of the simulated model, computed results were compared with experimental results, obtained by Aiyedun, *[1, 8].* This approach has been widely adopted by authors *[14, 20, 21].*

RESULTS AND DISCUSSIONS

The output of the program showing the temperature and Zener-Hollomon parameter values corresponding to various partitions in the through-thickness of AISI 316 Stainless Steel during hot flat rolling (using experimental data of Table I) are presented in Tables 2-6. A comparison between the calculated and measured result is carried out in Figure 3. Also, the computed results are illustrated graphically in Figures 4, 5, and 6.

Table 2: SPECIMEN NO. = P55
SPECIMEN HEIGHT = 16.18 mm
MEAN TEMPERATURE = 958.29 (C)

SN	Height (mm)	Temp. (C)	Zener-Hollomon Parameter Distribution (Log)
1	.00	798.57	21.64
2	.95	846.49	20.68
3	1.95	894.40	19.80
4	2.95	942.31	18.99
5	3.95	990.23	18.24
6	4.95	999.81	18.10
7	5.95	1009.39	17.96
8	6.95	1018.98	17.82
9	8.09	1038.14	17.54
10	9.09	1018.98	17.82
11	10.09	1009.39	17.96
12	11.09	999.81	18.10
13	12.09	990.23	18.24
14	13.09	942.31	18.99
15	14.09	894.40	19.80
16	15.09	846.49	20.68
17	16.18	798.57	21.64

Table 3: SPECIMEN NO. = P48
SPECIMEN HEIGHT = 15.88 mm
MEAN TEMPERATURE = 950.57 (C)

SN	Height (mm)	Temp. (C)	Zener-Hollomon Parameter Distribution (Log)
1	.00	792.14	21.85
2	.93	839.67	20.88
3	1.93	887.20	20.00
4	2.93	934.73	19.18
5	3.93	982.26	18.43
6	4.93	991.76	18.29
7	5.93	1001.27	18.15
8	6.93	1010.77	18.01
9	7.94	1029.79	17.73
10	8.94	1010.77	18.01
11	9.94	1001.27	18.15
12	10.94	991.76	18.29
13	11.94	982.26	18.43
14	12.94	934.73	19.18
15	13.94	887.20	20.00
16	14.94	839.67	20.88
17	15.88	792.14	21.85

Table 4: SPECIMEN NO. = P50
SPECIMEN HEIGHT = 16.08 mm
MEAN TEMPERATURE = 945.00 (C)

SN	Height (mm)	Temp. (C)	Zener-Hollomon Parameter Distribution (Log)
1	.00	795.00	21.77
2	.95	842.70	20.81
3	1.95	890.40	19.92
4	2.95	938.10	19.11
5	3.95	985.80	18.36
6	4.95	995.34	18.22
7	5.95	1004.88	18.07
8	6.95	1014.42	17.93
9	8.04	1033.50	17.66
10	9.04	1014.42	17.93
11	10.04	1004.88	18.07
12	11.04	995.34	18.22
13	12.04	985.80	18.36
14	13.04	938.10	19.11
15	14.04	890.40	19.92
16	15.04	842.70	20.81
17	16.08	795.00	21.77

Table 5: SPECIMEN NO. = P59
SPECIMEN HEIGHT = 12.10 mm
MEAN TEMPERATURE = 972.00 (C)

SN	Height (mm)	Temp. (C)	Zener-Hollomon Parameter Distribution (Log)
1	.00	810.00	21.43
2	.71	858.60	20.48
3	1.71	907.20	19.60
4	2.71	955.80	18.80
5	3.71	1004.40	18.05
6	4.71	1014.12	17.91
7	5.71	1023.84	17.77
8	6.71	1033.56	17.63
9	6.05	1053.00	17.36
10	7.05	1033.56	17.63
11	8.05	1023.84	17.77
12	9.05	1014.12	17.91
13	10.05	1004.40	18.05
14	11.05	955.80	18.80
15	12.05	907.20	19.60
16	13.05	858.60	20.48
17	12.10	810.00	21.43

Table 6: SPECIMEN NO. = P61
SPECIMEN HEIGHT = 7.83 mm
MEAN TEMPERATURE = 963.43 (C)

SN	Height (mm)	Temp. (C)	Zener-Hollomon Parameter Distribution (Log)
1	.00	802.86	21.68
2	.46	851.03	20.72
3	1.46	899.20	19.84
4	2.46	947.37	19.03
5	3.46	995.54	18.28
6	4.46	1005.18	18.14
7	5.46	1014.81	18.00
8	6.46	1024.45	17.86
9	3.92	1043.71	17.59
10	4.92	1024.45	17.86
11	5.92	1014.81	18.00
12	6.92	1005.18	18.14
13	7.92	995.54	18.28
14	8.91	947.37	19.03
15	9.91	899.20	19.84
16	10.92	851.03	20.72
17	7.83	802.86	21.68

As revealed in Tables 2 - 6 and Figures 3 and 4, a symmetrical pattern is observed in the computed temperatures and the Zener-Hollomon parameter values from the core of the material towards the rolling surfaces. This is in agreement with earlier works *[9, 12, 13, 14, 22]*.

A hot centre-chilled surface pattern is reflected by the temperature distribution, hence the observed higher surface strength in the material. This further confirms the roll chilling effect in AISI 316 Stainless Steel as earlier observed by Aiyedun *[1, 8].*

Hollomon parameter is from the rolling surfaces towards the core of the material. This implies that the material deforms increasingly towards the centre. This is further evident from Figure 5, where the Zener-Hollomon parameter decreases as rolling temperature rises towards the material's core. This is consistent with the fact that metals deform at a greater rate at elevated temperatures *[23]*.

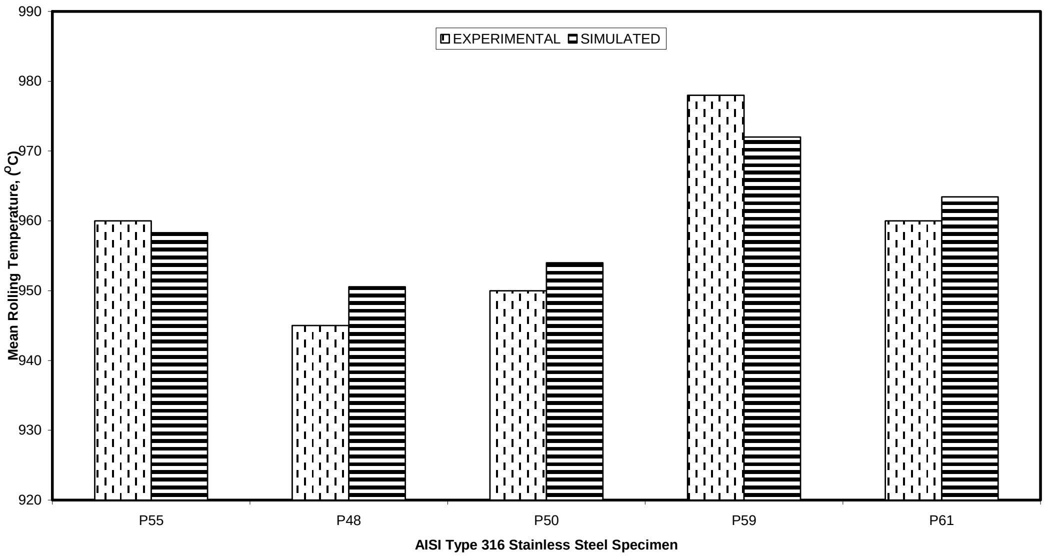

Figure 3: Comparison Between Experimental and Simulated Mean Rolling Temperature for Validating the Temperature Dependent Zener-Hollomon Parameter.

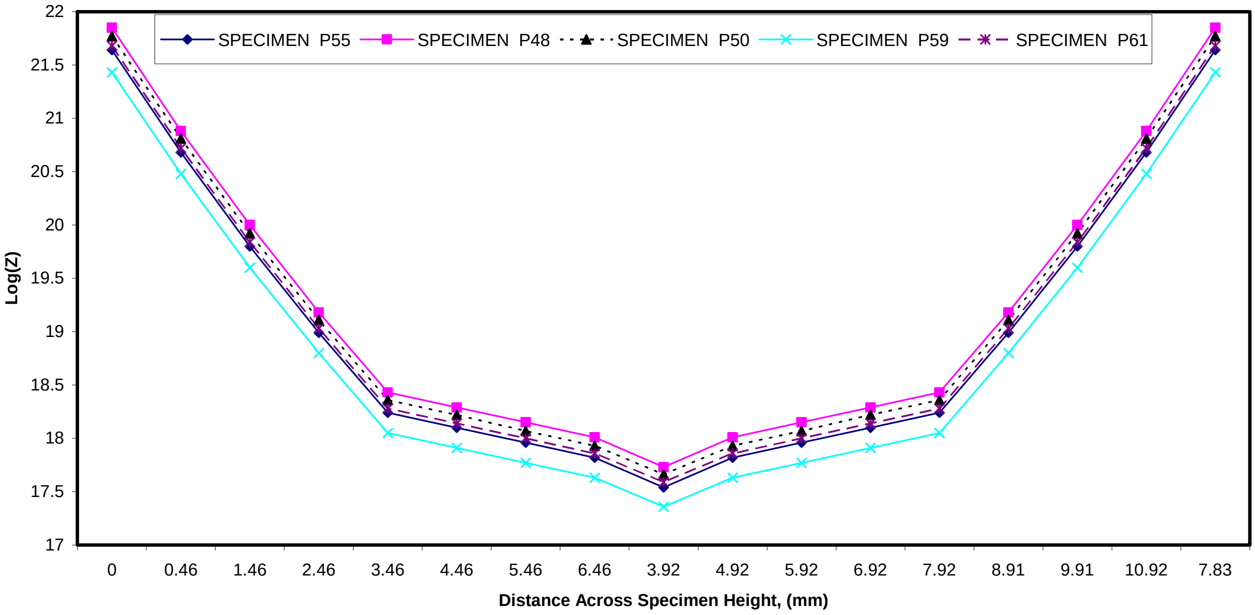

Figure 4: Variation of the Zener-Hollomon Parameter along Height of AISI 316 Stainless Steel During Hot Flat Rolling.

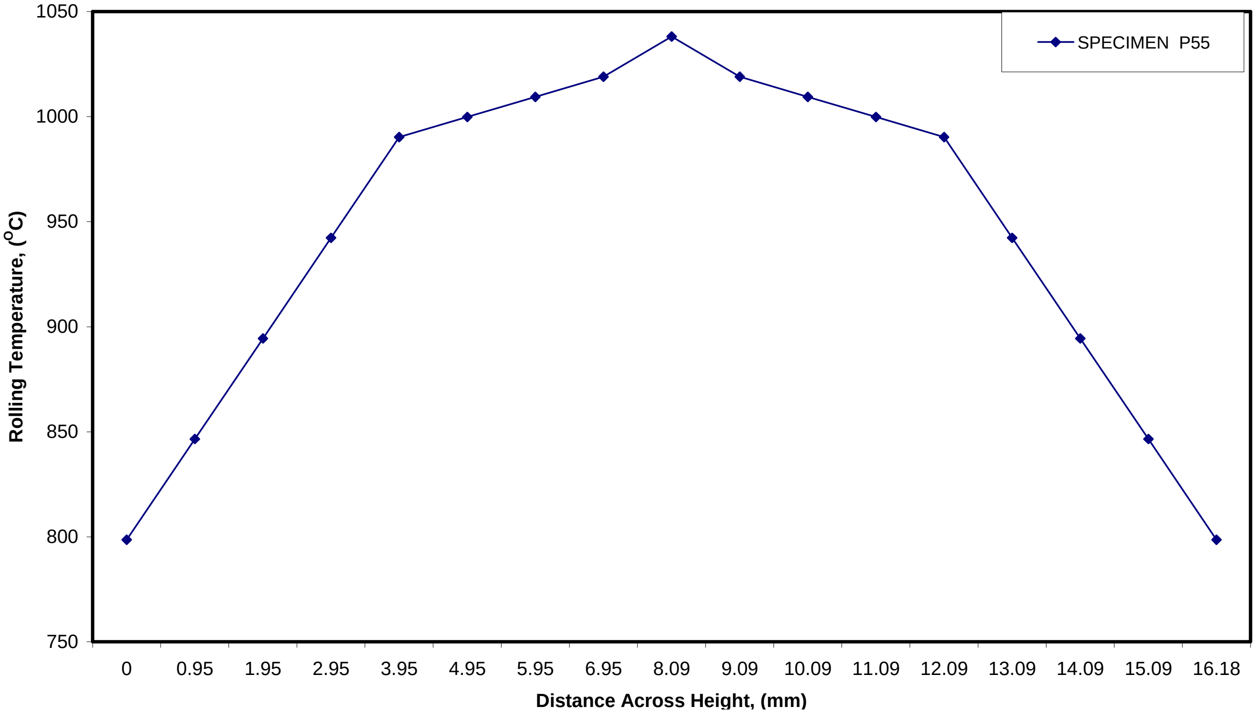

Figure 5: Temperature Distribution along the Height of AISI 316 Stainless Steel during Hot Flat Rolling.

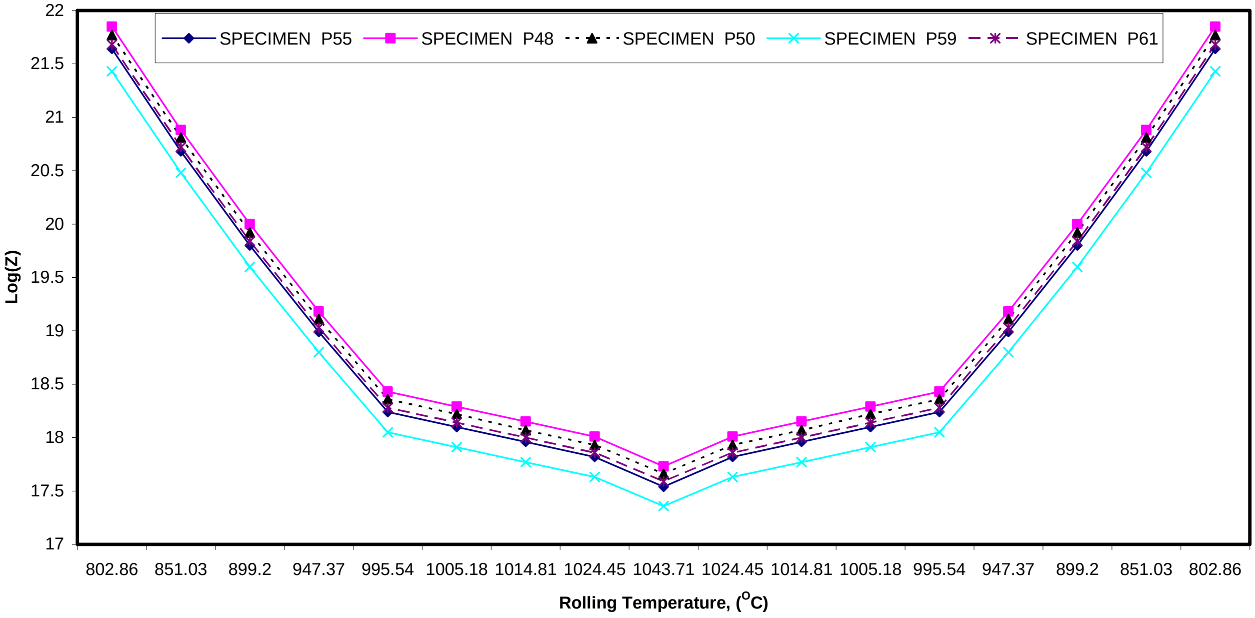

Figure 6: Variation of the Zener-Hollomon Parameter with Temperature during Hot Flat Rolling of AISI 316 Stainless Steel.

It is also evident from the results that the Zener-Hollomon parameter has a higher gradient at about a quarter of the specimens' thickness from the rolling surfaces. Towards the core, this gradient drops twice. This may be attributed to the phenomenon of in-homogeneity in deformation of metals during rolling process *[1, 8]*.

CONCLUSION

Hot rolling simulation of AISI 316 Stainless Steel using the Reverse Sandwich Model revealed a decrease in the Zener-Hollomon parameter values, in a symmetrical pattern, from the rolling surfaces towards the core of the material. This is an indication of an increasing deformation towards the mid-thickness of the material, since the slab temperature increases inwardly towards the core of the material. At zones close to the roll contact, lower gradients were observed in the Zener-Hollomon parameter.

APPENDIX – Simulation Program

```
C  Title     :  SIMULATION OF ZENER-HOLLOMON PARAMETER USING
RSM   *
C  Programer :  O. J. ALAMU                          *
C  Olabisi Onabanjo University, Ibogun Campus        *
C*******************************************************************
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION T(17),H(17),PLOT(17)
      CHARACTER TOLA*20, SPNO*6,RSPNS
      DATA IN/'N'/,IY/'Y'/
      Q=460000.0
      GKR=8.314
      P=132.0
      C=0.02474
C     FILES CREATION AND INTERACTIVE DATA ENTRY
      WRITE(*,*)'Enter a Filename for the Result.'
      READ(*,25)TOLA
      OPEN(UNIT=7,FILE=TOLA,STATUS='NEW')
   10 WRITE(*,*)'Supply the Specimen Identification Number.'
      READ(*,12)SPNO
      WRITE(*,*)'Enter the Roll Radius'
      READ(*,*)RO
      WRITE(*,*)'Supply the Rolling Speed.'
      READ(*,*)V
      WRITE(*,*)'Supply the Furnace Temperature of the Specimen.'
      READ(*,*)TF
      WRITE(*,*)'Supply the Initial Height of the Specimen.'
      READ(*,*)HO
      WRITE(*,*)'Enter the Final Height of the Specimen.'
      READ(*,*)HF
      WRITE(*,*) 'Enter the Width of the Specimen.'
      READ(*,*) W
      WRITE(7,*)'RESULTS OF THE PROGRAM'

WRITE(7,*)'@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
@@@'
   20 FORMAT(A1)
C     RELATIONSHIP BETWEEN ROLLING SPEED(V) AND THE RS
MODEL CONSTANT(K)
      IF(V.LE.10.0) THEN
      AK=1.59
      ELSE IF(V.LE.45.0) THEN
      AK=1.40
      ELSE IF(V.LE.100.0) THEN
      AK=1.19
      ELSE IF(V.LE.180.0) THEN
      AK=1.16
      ELSE IF(V.LE.250.0) THEN
      AK=1.12
      ELSE
      WRITE(7,*) "AK IS UNDEFINED"
      STOP
      END IF
C     CALCULATION OF REDUCTN(DEL), %REDUCTN(DELPER) &
DEFORMED ROLL RAD(DR)
      DEL = HO-HF
      DELPER=((HO-HF)/HO)*100
      DR = RO*(1+(C*P)/(DEL*W))
C     COMPUTATION OF MEAN TEMP(TMEAN),SURFACE
TEMP(TE),TEMP DISTRIBUTN
               (TDIST), MIDDLE TEMP(TMID) & TEMP VAR ALONG
THICKNESS (T1..T17)
      TMEAN = (TF+(TF/AK))/2.0
      TMID = (TMEAN+TF)/2.0
      TE = TF/AK
      TDIST = TMID-TE
      T(1) =TE
      DO 7 J=1,4
    7 T(J+1) = T(J)+0.2*TDIST
      DO 8 J=5,7
    8 T(J+1) = T(J) +0.04*TDIST
      T(9) = (TMEAN+TF)/2.0
      M=0
      DO 9 J=8,5,-1
      M=M+1
    9 T(J*2)=T(M*2)
      M1=3
      DO 11 J=15,11,-2
      T(J)=T(M1)
   11 M1=M1+2
      T(17)=T(1)
C     COMPUTATION OF STRAIN RATE
      SRT = ((1.08*V)/(DR*DEL)**0.5)*((DEL/(HO*HF))**0.25)*(ALOG(HO/HF)
     1)**0.45
C     ESTIMATN THICKN VAR CORR.TO TEMP VARIATION (H1..H17)
ALONG HEIGHT
      H(1) = 0
      H(2) = HO/17.0
      DO 13 J=2,16
      IF(J.EQ.8) THEN
      H(J+1) = HO/2.0
      ELSE IF (J.EQ.16) THEN
      H(J+1) = HO
      ELSE
      H(J+1) = H(J)+1
      END IF
   13 CONTINUE
C     ESTIMATION OF ZENER HOLLOMON PARAMETER ALONG
THICKNESS
      DO 15 J = 1,17
      PLOT(J) = ALOG10(SRT*DEXP(Q/(GKR*(T(J)+273))))
   15 CONTINUE
   25 FORMAT(A4)
   26 FORMAT(1X,'SPECIMEN NO. =     'A4,/1X,'SPECIMEN HEIGHT =
'F5.2)
   27 FORMAT(1X,'MEAN TEMPERATURE =      'F7.2,1X,'(`C)')
```

```
  28 FORMAT(1X,I2,6X,F5.2,6X,2F8.2)
    WRITE(7,26)SPNO,HO
    WRITE(7,27)TMEAN

WRITE(7,*)'_____________________________________________________________'
    WRITE(7,*)'SNO      HEIGHT      TEMPERATURE   ZENER-
HOLLOMON'
    WRITE(7,*)'        (mm)        DISTRIBUTION  PARAMETER'
    WRITE(7,*)'                    (`C)         (LOG)'

WRITE(7,*)'______________________________________________________________'
    DO 88 J=1,17
  88 WRITE(7,28)J,H(J),T(J),PLOT(J)

WRITE(7,*)'_______________________________________________________________'
    WRITE(*,29)TOLA
  29 FORMAT(1X,13HEnter,  edit  ,A14,29Hfor the output of the program)
  30 WRITE(*,*)'DO YOU WISH TO CONTINUE?(Y/N)'
    READ(*,20)RSPNS
    IF(RSPNS.EQ.IY) GO TO 10
    IF(RSPNS.EQ.IN) GO TO 31
    WRITE(*,*)'INVALID RESPONSE !! ENTER (Y/N) USING UPPERCASE
LETTER'
    GO TO 30
  12 FORMAT(A4)
  31 STOP
    END
C************************************************************************
```

REFERENCES

1. Aiyedun, P.O. 1984. “A Study of Loads and Torque for Light Reduction in Hot Flat Rolling at Low Strain Rates”. Ph.D. Thesis. University of Sheffield.

2. El-Kalay, A.K.E.H.A. and Sparling, L.G.M. 1968. “Factors Affecting Friction and their Effect upon Load, Torque, and Spread in Hot Flat Rolling”. *Jnl. of the Iron and Steel Institute*l. 206:152-163.

3. Beese, J.G. 1972. “Ratio of Lateral Strain to Thickness Strain during Hot Rolling of Steel Slabs”. *Jnl. of the Iron and Steel Institute*. 210:433-436.

4. Chikara, N.L. and Johnson, W. 1966. “Some Experimental Results concerning Spread in the Rolling of Lead”. *Jnl. of Basic Engineering*. 8: 489-499.

5. Oyinlola, A.K. 1990. “Photoplastic Analysis of Strain Distribution in Three-Dimensional Deformation in the Hot Rolling of Aluminium”. *Ife Journal of Technology*. 2(2):13-20.

6. Schey, J.A. 1966. “Prevention of Edge Cracking in Rolling by means of Edge Restraints”. *Jnl. of the Institute of Metals*. 94:193-200.

7. Afonja, A.A. and Sansome, D.H. 1973. “A Theoretical Analysis of the Sandwich Rolling Process”. *Int. J. Mech. Sci.* 15:1 – 14.

8. Aiyedun, P.O. 1986. “Hot Flat Rolling Simulation by Use of the Bland and Fords Cold Rolling Theory for HCSS316 at Low Reduction and Low Strain Rates”. *Proc, Int. AMSE Conf.* 3:14 – 36.

9. Alamu, O.J. and Aiyedun, P.O. 2001. “A Comparison of Temperature Gradient in Hot Rolling at Low and High Strain Rates”. *J. Sci. Engr. Tech.* 10(1):4644 – 4654.

10. Arnold, R.R. and Whitton, P.W. 1959. “Stress and Deformation Study for Sandwich Rolling Hard Metals”. *Proc. Instn. Mech. Engrs.* 3 – 13.

11. Atkins, A.G. and Weinstein, A.S. 1970. “The Deformation of Sandwich Materials”. *Int. J. Mech. Sci.* 12:641 – 657.

12. Shobowale, B. 1998. “The Reverse Sandwich Effect in HCSS316 Hot Flat Rolled at Low Strain Rates and Low Reductions”. M.Sc. Thesis, University of Ibadan, Ibadan, Nigeria.

13. Alamu, O.J. 2001. “Integration of the Reverse Sandwich Model into the Hot Rolling Bland and Ford’s Theory for Load and Torque Calculations”. M.Sc. Thesis, University of Ibadan, Ibadan, Nigeria.

14. Alamu, O. J., 2002. “Simulation of Temperature Gradient in Hot Flat Rolling at Low Strain Rates”. *Journal of Science and Technology Research*. 1(1):55 – 66.

15. Serajzadeh, S., Taheri, A.K., and Mucciardi, F. 2002. “Prediction of Temperature Distribution in the Hot Rolling of Slabs”. *Modelling Simul. Mater. Sci. Eng*. 10:185-203.

16. Alamu, O.J. and Aiyedun, P.O. 2003. “The Influence of Ingot Geometry on Temperature Distribution in HCSS316 During Hot Rolling”. *Lautech Journal of Eng. and Technology*. 1(1):47 - 63.

17. Alamu, O.J. and Aiyedun, P.O. 2003. “A Comparison of Temperature Distribution in Hot Rolling at Low and High Strain Rates”. *J. Sci. Engr. Tech.* 10(1):4644 - 4654.

18. Sims, R.B. 1954. “The Calculation of Roll Force and Torque in Hot Rolling Mills”. *J.I.S.I.* 191.

19. Farag, M.M. and Sellars, C.M. 1979. “Hot Working and Forming Processes”. Proc. Metals Society Conference. Sheffield.

20. Guerrero-Mata, M.P., Zambrano, P.C., Colas, R., and Leduc, L.A. 2003. “Mathematical Modelling of the Production of a Compact Hot Rolling Mill”. *Revista de la Facultad de Ingenieria de la U.C.V.* 18(2):39-45.

21. Jiang, Z.Y. and Tieu, A.K. 2000. “Modelling of Rolling of Strips with Longitudinal Ribs by 3-D Rigid Visco-plastic Finite Element Method”. *ISIJ International.* 40(4):373-379.

22. Ojediran, J.O., Alamu, O.J., and Idowu, O. 2002. “Effect of Rolling Reduction on Temperature Gradient in Hot Flat Rolling of HCSS316”. *Journal of Engineering* Application. 4(1):1-13.

23. Early, J.G. 1977. “Elevated Temperature Mechanical Behaviour of a Carbon-Manganese Pressure Vessel Steel”. *Journal of Engineering Materials and Technology*. 359 – 365.

ABOUT THE AUTHORS

Dr. Oguntola Jelil Alamu is the current Head of Department of Mechanical Engineering, University of Agriculture, Abeokuta, Nigeria. He holds a Ph.D. in Mechanical Engineering. His research interests are in renewable energy and materials science & engineering.

Mr. Solomon Olanrewaju Giwa is a Lecturer in the Department of Mechanical Engineering, Olabisi Onabanjo University, Ago-Iwoye, Nigeria. His research interests are in manufacturing science and energy studies.

Mr. M.A. Sulaiman is a researcher in the Department of Mechanical Engineering, Olabisi Onabanjo University, Ago-Iwoye, Nigeria. His research interests are in manufacturing science.

Dr. Christopher Chintua Enweremadu is a Lecturer in the Department of Mechanical Engineering, Ladoke Akintola University of Technology, Ogbomoso, Nigeria. He holds a Ph.D. in Mechanical Engineering. His research interests are in renewable energy and machine design.

Mr. Idris Adekunle Lateef is a Lecturer in the Department of Mechanical Engineering, Osun State College of Technology, Esa-Oke, Nigeria. His research interests are in manufacturing technology and automobile engineering.

SUGGESTED CITATION

Alamu, O.J., S.O. Giwa, M.A. Sulaiman, C.C. Enweremadu, and I.A. Lateef. 2008. “The Zener-Hollomon Parameter Characteristics in Hot Rolling of AISI 316 using the Reverse Sandwich Model”. *Pacific Journal of Science and Technology*. 9(1):163-172.

Pacific Journal of Science and Technology