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Simulation of Temperature Distribution in Hot Flat Rolling at Low Strain Rates

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Abstract: ***The technique of sandwich rolling of metals into thinner gauges brings about considerable rolling load economy, stemming the distortion tendency of the rolls which results from excessive roll forces through direct rolling of high strength metal sheets. Authors have however confirmed a persistent excessive rolling load and torque in hot flat rolling at low strain rates (0.01 – 1.5) s^{-1}. This "reverse sandwich effect" observed in the hot rolling of steel has been attributed to precipitation hardening and a possible temperature gradient in the material when rolled at low strain rate. This paper investigates the temperature distribution pattern along the height of High Carbon Stainless Steel type 316 during hot flat rolling at low strain rates. Hot Rolling Temperature Distribution (HRTD) program was written in FORTAN 77 languages for simulation of the Reverse Sandwich Model (RSM) developed for the material. Results of the program, using experimental data, show a symmetrical temperature gradient from the rolling surfaces to the middle of the specimen. This justifies the higher load and torque on the rolls. The output of the program compares favorably with experimental results.***

Keywords: Temperature, Rolling, High Carbon Steel, Reverse Sandwich

1. Introduction

Forming processes are generally classified as hot working or cold working based on both the material being formed and the temperature. In hot working, such as rolling, the deformation is performed under conditions of temperature and strain rate where recrystallization occurs simultaneously with the deformation. To achieve this, the temperature of deformation is usually in excess of 0.6 times the melting point of the material on an absolute temperature scale [1] .

The success or failure of a hot deformation process often depends on the ability to control the temperatures within the work piece. Over 90% of the energy imparted to a deforming work – piece will be converted into heat. Hot rolling of metals involves deformation of metals between two revolving rolls at temperatures above the recrystallization temperature of the metal. This process is typical of other hot forming processes. Here, less roll force is required and higher production speed is achieved [1]. As with all hot – working processes, temperature control is crucial to the success of the hot – rolling process.

The cold working of high strength metals and alloys into thin gauges in conventional rolling plant causes excessive distortion (flattening) of the rolls. This is due to the considerable rolling load involved [2,3]. An alternative is the sandwich rolling technique, which involves rolling of high strength materials sandwich between layers of softer material on the ordinary rolling plant [4,5]. This technique offers the advantages of load economy and increase in reductions achievable between anneals. A reverse situation to sandwich rolling, attributed to temperature variation along the material's thickness during rolling has been confirmed to exist naturally in hot rolling of metals at low strain rates and low reductions [6]. This has further been confirmed through the integration of the Reverse Sandwich Model developed for High Carbon Stainless Steel (HCSS) type 316 into the Hot Rolling Bland and Ford's Theory [7]. This work presents a simulation of the Reverse Sandwich Model (RSM), which predicts the local temperature variation at different zones along the height of HCSS316 during hot rolling at low strain rates (0.01 – 1.5) s^{-1}.

2. Material and Method

2.1 Temperature Distribution Model

The reverse sandwich rolling presents a situation whereby a high strength - metal clads a low strength metal. In this case the strength differentiation is as a result of drastic temperature variation during rolling. This phenomenon has been found to be applicable to the hot rolling of HCSS316 at low strain rates and low reduction [6,7,8]. The following is a model, based on the reverse sandwich effect [8], predicting the temperature distribution in this material during hot rolling.

2.2 Rolling Temperature Distribution

The temperature at the middle of the specimen is given as: (Shobowale, 1998)

$$T_{MID} = \frac{T_{MEAN} - T_f}{2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where: T_{MEAN}, the mean rolling temperature is given as:

$T_{MEAN} = ½ [T_f + T_s]$ …………………… (2)

where; the exit surface temperature,

$$T_S = \frac{T_f}{K} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

and K = the reverse sandwich model constant.

The rolling temperature distribution from the middle to the surface of the material is given by equation (4).

$T_{DIST} = T_{MID} – T_S$ …………………. (4)

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The Reverse Sandwich Model constant, K is a function of the rolling speed, V; for low reductions, the two parameters are related as follows:

$$\left.\begin{array}{lll} \text{For} & 9 \le V \le 10, & K = 1.59 \\ & 10 \le V \le 45, & K = 1.40 \\ & 45 \le V \le 100, & K = 1.19 \\ & 100 \le V \le 180, & K = 1.16 \end{array}\right\} \quad \ldots(5)$$

where,
V is measured in mms^{-1}
The reverse sandwich model constant is used in estimating the exit surface temperature of the rolled material according to equation (3).

In this model the specimen being rolled is partitioned into 17 zones.
The model's prediction of temperature for seventeen zones of the specimen thickness follows equation (6) to (8) as follows:
For $1 \le n \le 4$ and $15 \ge n \ge 12$,
$T_{n+1} = T_n + 0.2\, T_{DIST}$ ………………………….. (6)

For $8 < n < 9$,
$T_{n+1} = T_{DIST}$ ……………………….. (7)

For $5 \le n \le 7$ and $11 \ge n \ge 9$,
$T_{n+1} = T_n + 0.04\, T_{DIST}$ ……………… (8)

Height of Specimen
The corresponding heights along thickness for the temperature distribution were modeled thus [7]:
$h_1 = 0$ ………………….. (a)
$h_2 = Ho/17$ …………………. (b)
For $2 \le n \le 7$,
$h_{n+1} = h_n + 1$ …………………. (c)
For $7 < n < 9$, …………….. (9)
$h_n = Ho/2$ …………………. (d)
For $15 \ge n \ge 9$,
$h_{n+1} = h_n + 1$ …………………. (e)
For $15 < n < 17$,
$H_{n+1} = H_f$ …………………. (f)

$$\left.\begin{array}{lll} & h_1 = 0 & \ldots\ldots\ldots\ldots\ (a) \\ & h_2 = Ho/17 & \ldots\ldots\ldots\ldots\ (b) \\ \text{For} & 2 \le n \le 7, & \\ & h_{n+1} = h_n + 1 & \ldots\ldots\ldots\ldots\ (c) \\ \text{For} & 7 < n < 9, & \\ & h_n = Ho/2 & \ldots\ldots\ldots\ldots\ (d) \\ \text{For} & 15 \ge n \ge 9, & \\ & h_{n+1} = h_n + 1 & \ldots\ldots\ldots\ldots\ (e) \\ \text{For} & 15 < n < 17, & \\ & H_{n+1} = H_f & \ldots\ldots\ldots\ldots\ (f) \end{array}\right\} \ldots\ (9)$$

3. Simulation of the Model

The model presented in the preceding section was developed into a computer program, hereto named the Hot Rolling Temperature Distribution (HRTD) program. The simulation was carried out using FORTRAN 77. In running the program, four test specimens were considered with varying heights, roll radius, rolling speed and furnace temperatures. These test data, presented in Table I, was obtained from the experimental work carried out on High Carbon Stainless Steel (HCSS) type 316 (with Niobium and vanadium inclusion), hot flat rolled at low strain rates $(0.01 – 1.5)s^{-1}$ and low reduction (≈ 10%) on two high reversing laboratory mills of roll diameters 254.0mm and 139.7mm respectively. Data for the four specimens H24, H30, P58 and P43 were fed into the program, in turn, in a computer – user interactive form.

4. Results and Discussion

A test run of the Hot Rolling Temperature Distribution (HRTD) program, using data from Table I, are Presented in Table II (a – d). Graphical descriptions of the results are as shown in Fig. I. From the tables and the figure, symmetry is observed in the temperature distribution from the two rolling surfaces to the middle of the specimen. The observed pattern is that of increase in temperature from the surface to the center of the material.

Table II presents a comparison between the result of the HRTD program and experimental results obtained by Aiyedun [2,6]. From the table, the results of the simulation are in very good agreement with experimental results with percentage deviations of 2.99, 2.56, 2.31 and 2.20 for specimens H37, H22, P58 and P41 respectively. The strength of a material during rolling depends largely on temperature and strain rates. For hot rolling, changes in the rolling speed bring about changes in the strain rates which are manifested in terms of pronounced temperature effects. The temperature variation observed for rolling at low speeds (about 9.31 – 21.01)mms^{-1} (strain rates of about 0.08 – 0.22)s^{-1} as revealed through Fig. I, showed a high temperature gradient penetrating deep into the specimen height giving a high mean temperature drop at the rolling surfaces.

Thus, a colder surface and hot centre pattern of temperature distribution is obtained for the specimens. It is evident from this result that at low strain rates, there is a drastic temperature gradient from the much colder surface to the hot center, hence the surface of the metal is sufficiently chilled enough to effect a reduction in the bulk mean temperature. Based on the significant effect of temperature on the yields stress and hence, on rolling load and torque, a higher surface strength compared to a lower middle strength is created. This further explains the reverse sandwich effect observed in High Carbon Stainless Steel (HCSS316). Results obtained from this computer simulation are in agreement with earlier works [6,7,8,9].

5. Conclusion

Computer simulation of the reverse sandwich model carried out quantitatively revealed an increasing temperature from the rolling surfaces of the material to a peak value at the core. At low strain rates, the temperature gradient is uniform, giving an appreciable mean temperature drop at the surfaces; confirming a higher strength surface - lower strength core in HCSS316 during hot rolling. Results obtained are consistent with earlier works of other researchers.

Table 1: Input Data for the Program

Specimen	*Roll Radius (mm)*	*Height (mm)*	*Rolling Speed (mms^{-1})*	*Furnace Temperature (^oC)*
H37	127.00	15.96	9.31	1122
H22	127.00	15.98	19.51	1056
P58	69.85	14.02	21.01	1142
P41	69.85	15.96	18.73	1190

Table 2: Comparison of Results with Experimental Values.

Specimen	Experimental Mean Rolling Temperature (^oC)	Predicted Mean Rolling Temperature (^oC)	Percentage Deviation (%)
H37	942.0	913.83	2.99
H22	929.0	905.14	2.56
P58	1002.0	978.86	2.31
P41	1043.0	1020.24	2.20

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C****************************************
***************
C HOT ROLLING TEMPERATURE DISTRIBUTION
PROGRAM
C****************************************
***************

 IMPLICIT REAL*8(A-H,O-Z)
 DIMENSION T(17),H(17)
 CHARACTER TOLA*20,SPNO*6,RSPNS
 DATA IN/'N'/,IY/'Y'/

 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(*,*)'Supply the Rolling Speed.'
 READ(*,*)V
 WRITE(*,*)'Supply the Furnace
Temperature.'
 READ(*,*)TF
 WRITE(*,*)'Supply the Initial Height of
the Specimen.'
 READ(*,*)HO
 WRITE(7,*)
 WRITE(7,*)
 WRITE(7,*)'ROLLING TEMPERATURE
DISTRIBUTION'

WRITE(7,*)'@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
@@@'

 20 FORMAT(A1)

C RELATIONSHIP BETWEEN ROLLING SPEED(V)
AND THE REVERSE SANDWICH
C ROLLING 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
 ENDIF

C COMPUTATION OF MEAN TEMPERATURE,
SURFACE TEMPERATURE,
C TEMPERATURE DISTRIBUTION, MIDDLE
TEMPERATURE, AND
C TEMPERATURE DISTRIBUTION ALONG
MATERIAL 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 ESTIMATION OF THICKNESS VARIATION
CORRESPONDING TO TEMPERATURE
C 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
 25 FORMAT(A14)
 26 FORMAT(1X,'SPECIMEN NO. =
'A4,/1X,'SPECIMEN HEIGHT = 'F5.2)
 27 FORMAT(1X,'MEAN TEMPERATURE = 'F7.2)
 28 FORMAT(1X,I2,6X,F5.2,6X,F8.2)
 WRITE(7,26)SPNO,HO
 WRITE(7,27)TMEAN

WRITE(7,*)'____________________________
____'
 WRITE(7,*)'SNO HEIGHT TEMPERATURE '
 WRITE(7,*)' (mm) DISTRIBUTION '

WRITE(7,*)'____________________________
____'
 DO 88 J=1,17
 88 WRITE(7,28)J,H(J),T(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*************************************
********************************
```

Table II: Program Result

(a)

ROLLING TEMPERATURE DISTRIBUTION
@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
SPECIMEN NO. = H37
SPECIMEN HEIGHT = 15.96
MEAN TEMPERATURE = 913.83

SNO	HEIGHT (mm)	TEMPERATURE DISTRIBUTION
1	.00	705.66
2	.94	768.11
3	1.94	830.56
4	2.94	893.01
5	3.94	955.46
6	4.94	967.95
7	5.94	980.44
8	6.94	992.93
9	7.98	1017.92
10	8.98	992.93
11	9.98	980.44
12	10.98	967.95
13	11.98	955.46
14	12.98	893.01
15	13.98	830.56
16	14.98	768.11
17	15.96	705.66

(b)

ROLLING TEMPERATURE DISTRIBUTION
@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
SPECIMEN NO. = H22
SPECIMEN HEIGHT = 15.98
MEAN TEMPERATURE = 905.14

SNO	HEIGHT (mm)	TEMPERATURE DISTRIBUTION
1	.00	754.29
2	.94	799.54
3	1.94	844.80
4	2.94	890.06
5	3.94	935.31
6	4.94	944.37
7	5.94	953.42
8	6.94	962.47
9	7.99	980.57
10	8.99	962.47
11	9.99	953.42
12	10.99	944.37
13	11.99	935.31
14	12.99	890.06
15	13.99	844.80
16	14.99	799.54
17	15.98	754.29

(c)
ROLLING TEMPERATURE DISTRIBUTION
@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
SPECIMEN NO. = P58
SPECIMEN HEIGHT = 14.02
MEAN TEMPERATURE = 978.86

SNO	HEIGHT (mm)	TEMPERATURE DISTRIBUTION
1	.00	815.71
2	.82	864.66
3	1.82	913.60
4	2.82	962.54
5	3.82	1011.49
6	4.82	1021.27
7	5.82	1031.06
8	6.82	1040.85
9	7.01	1060.43
10	8.01	1040.85
11	9.01	1031.06
12	10.01	1021.27
13	11.01	1011.49
14	12.01	962.54
15	13.01	913.60
16	14.01	864.66
17	14.02	815.71

(d)
ROLLING TEMPERATURE DISTRIBUTION
@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
SPECIMEN NO. = P41
SPECIMEN HEIGHT = 15.96
MEAN TEMPERATURE = 1020.00

SNO	HEIGHT (mm)	TEMPERATURE DISTRIBUTION
1	.00	850.00
2	.94	901.00
3	1.94	952.00
4	2.94	1003.00
5	3.94	1054.00
6	4.94	1064.20
7	5.94	1074.40
8	6.94	1084.60
9	7.98	1105.00
10	8.98	1084.60
11	9.98	1074.40
12	10.98	1064.20
13	11.98	1054.00
14	12.98	1003.00
15	13.98	952.00
16	14.98	901.00
17	15.96	850.00

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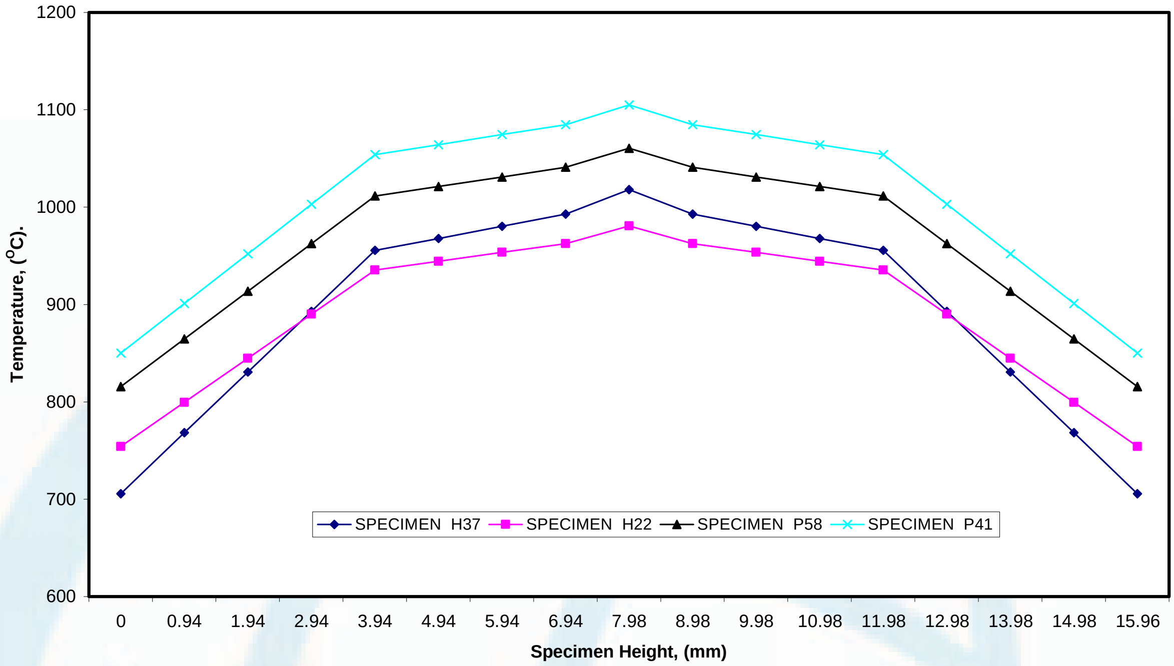

FIG. 1: TEMPERATURE VARIATION WITH HEIGHT DURING THE HOT ROLLING OF HCSS316 AT LOW STRAIN RATES