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THE INFLUENCE OF INGOT GEOMETRY ON TEMPERATURE DISTRIBUTION IN HCSS316 DURING HOT ROLLING

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ABSTRACT

The effects of material geometry on rolling parameters such as yield stress, rolling load and torque have been studied. In this work, geometrical variation is introduced into the Reverse Sandwich Rolling Model (RSM) for high carbon stainless steel type 316 (HCSS316). The modification affords evaluation of the possible effect of geometry of the in-going strip of HCSS316 on temperature distribution in the material during hot rolling. Simulation of the model was carried out using FORTRAN 77. The computer code was validated with hot rolling experimental data from two high – reversing hot rolling mills with different roll diameter. Results of the simulation revealed a symmetrical temperature distribution from the rolling surfaces, to the mid-thickness of the specimen where it peaked. This pattern was consistent for specimens with different geometry. The results showed agreement with experimental inferences.

Keywords: Geometry, Reverse Sandwich Model, Rolling, Temperature

INTRODUCTION

Rolling is the first process that is used to convert metals into finished wrought products, which are subsequently reduced in size and converted into basic forms such as sheets, rods and plates. This process involves passage of heated metal between two rolls that rotate in opposite directions (Fig.1 (a)). The working of high strength metals and alloys into thin gauges causes excessive distortion of the rolls (Afonja and Sansome, 1973). Rolling of high strength materials sandwiched between layers of softer material, known as sandwich rolling, evolved as alternative technique devoid of roll distortion (Arnold and Whitton, 1959; Atkins and Weinstein, 1970). This rolling technique has been practised in industry for many years in the production of limited quantities of expensive, high – strength sheets (Afonja and Sansome, 1973).

However, a reverse situation to sandwich rolling has been confirmed to exist in High carbon stainless steel 316 (HCSS316) when hot rolled at low strain rates and low reductions (Aiyedun, 1984, 1986). Here, high strength surfaces clad a low strength core (Fig. 1(b)). This has been attributed to a possible temperature gradient in the through – thickness of the material and precipitation hardening (Aiyedun, 1986). Hence, the Reverse Sandwich Model, (RSM) which predicts rolling parameters such as temperature, yield stress, load, Zenner – Holomon parameter and load at different zones in the through-thickness of HCSS316 during hot rolling, was developed (Shobowale, 1998).

Studies on the effects of different parameters on the hot rolling characteristics of metals and alloys have been enhanced through computer models. Anthonio and Renato, (1996) studied the effect of the finish rolling temperature and cooling rate on the development of the microstructure and mechanical properties of a Mn-Si-Cr-Mo dual-phase steel suitable for hot rolling using computer models. Similarly, the American Iron and Steel Institute (AISI) recently funded a research on micro structural studies on hot strip rolling, where a user-friendly mathematical model describing the through - thickness thermal and micro structural changes during hot rolling was developed. The models, capable of predicting final mechanical properties for High Strength Low Alloy (HSLA) steel grades, were validated with data obtained from testing conducted on the steel grades using Gleeble and Torsion machines. The predictions were validated by comparison with measurements from rolling mills (Tapestry, 1999).

For HCSS316, Aiyedun (1984) confirmed that specimen geometry does not have systematic effect on rolling load. Shobowale, (1998) also confirmed that variation in geometry of this material has no systematic effect on yield stress and the rolling load. However, Barraclough et al (1973) studied the effect of specimen geometry on hot torsion test results and found out that for dynamically crystallizing materials, strain peak stress increases as the gauge length / radius ratio decreased below 2.0.

This work is therefore aimed at investigating the possible effect of geometry of HCSS316 ingot on the temperature distribution pattern in the material during hot rolling. Geometrical variations will be introduced into the Reverse Sandwich Model through different width-height (w/h) ratio of the specimen (Fig.1(c)). The modified model will then be simulated and validated with hot rolling experimental data for different hot rolling schedules.

Background to the Study

Rolling Theories

Lennard, 1980, reported that Sim's theory is generally adopted as a theory of hot rolling, characterized with sticking throughout the roll gap, while the Bland and Fords theory is basically a theory for cold rolling, where sliding takes place throughout the arc of contact. The latter has however been found applicable to hot rolling of HCSS 316, where there is a mixed sticking - sliding condition (Aiyedun 1984; Ayedun and Sellars, 1998). This is the situation for hot rolling of HCSS316 at 900°C – 1200°C, (0 – 15) % reductions and (0.07 – 1.5) s^{-1} strain rates.

Temperature Estimation during Hot Rolling

During hot rolling, the strain rate effects, especially at low values (0.01 -1.5) s^{-1}, change contact times with the rolls and are manifested in terms of pronounced temperature effects. Temperature distributions are predicted by solving the differential equation that governs heat flow through two-dimensional finite difference computer model (Aiyedun, 1986).The general validity of the model have been confirmed by rolling Aluminum, Lead, and Steels with good agreement between the predicted and observed temperatures (Aiyedun, 1984). Adopting similar approach, and in order that the pitfall of assuming an average rolling temperature for the through- thickness of HCSS316 be avoided, especially at low strain rate (Aiyedun, 1984), the RSM was developed (Shobowale, 1998).

MATERIALS AND METHODS

The Reverse Sandwich Model is modified to accommodate geometry variation in the in-going strip. The modified model presented below was simulated using FORTRAN 77, to generate results which were further processed with the EXCEL package, to reveal any possible influence of ingot geometry on temperature distribution pattern in HCSS316 during hot rolling.

The Modified Reverse Sandwich Model

The Reverse Sandwich Model has been fully described by Shobowale, (1998), Alamu, (2001) and Alamu and Aiyedun, (2002). In this work, only the portion on temperature distribution as well as the introduced geometrical model is presented.

The temperature at the core (mid thickness) of the specimen is given as:

$$T_{CORE} = \frac{1}{2}(T_M - T_f) \quad \ldots\ldots \quad 1$$

where: T_f = furnace temperature, T_M = the mean rolling temperature

$$T_M = \frac{1}{2}(T_f - T_s)] \quad \ldots\ldots \quad 2$$

Where: T_s = exit surface temperature,

$$T_s = \frac{T_f}{K} \quad \ldots\ldots \quad 3$$

where; K = Reverse Sandwich Model constant, values of which are functions of the rolling speed.

Thus: for

$$\left.\begin{array}{l} 9 \le v \le 10, K = 1.59 \\ 10 \le v \le 45, K = 1.40 \\ 45 \le v \le 100, K = 1.19 \\ 100 \le v \le 180, K = 1.16 \end{array}\right\} \quad \ldots \quad 4$$

where, V is measured in mms^{-1}.

In the model, the ingot thickness was partitioned into 17 zones [Fig.1(c)] as follows

$$\left.\begin{array}{ll} & h_1 = 0 \\ & h_2 = Ho/17 \\ \text{for} & 2 \le n \le 7 \\ & h_{n+1} = h_n + 1 \\ \text{for} & 7 < n < 9 \\ & h_n = Ho/2 \\ \text{for} & 15 \ge n \ge 9 \\ & h_{n+1} = h_n + 1 \\ \text{for} & 15 < n < 17 \\ & H_{n+1} = H_n \end{array}\right\} \quad \ldots\ldots \quad 5$$

The model's prediction of temperature in these zones are:

$$\left.\begin{array}{ll} \text{for} & 1 \le n \le 4 \text{ and } 15 \ge n \ge 12, \\ & T_{n+1} = T_n + 0.2\,T_{DIST} \\ \text{for} & 8 < n < 9 \\ & T_{n+1} = T_{DIST} \\ \text{for} & 5 \le n \le 7 \text{ and } 11 \ge n \ge 9, \\ & T_{n+1} = T_n + 0.04\,T_{DIST} \end{array}\right\} \quad 6$$

From Fig.1(c), ingot geometry can be varied with varying width – height ratio (geometry factor), here defined as :

$$f_g = \frac{w}{h} \quad \ldots\ldots \quad 7$$

where : f_g = geometric factor,

w_0 = initial width of the ingot,

h_0 = initial height of the rolled material.

Experimental

To generate a database for validating the simulation of the modified RSM, preliminary metallographic, hot torsion tests, and hot rolling experiments were performed on the as-received wrought HCSS316 (with Nb, V and Ti inclusions) in the temperature range (600–1200) ^{O}C and strain rate range of (3.6X10^{-3} – 1.4) s^{-1}. The wrought material was High Carbon Stainless Steel; ASME SA-240 from Heat 38256-2C, product of G. O. Carlson Inc., P.A., U.S.A. The chemical composition of HCSS316 and results of the preliminary study on the as received material are as shown in Table I. The material was cut into slabs of small sizes and hot rolled. The hot rolling experiments were performed on two laboratory mills; a 1000kN, 2-high, single stand, reversible mill with rolls of 254.0mm diameter by 266.0mm barrel length and 50T (498kN) capacity, 2-high reversible, Hille 50T rolling mill with rolls of diameter 139.7mm.

Simulation of the Model

The geometric factor of equation (7) was integrated into the Reverse Sandwich Model. Simulation of the new model (described in (1) – (7) above) was carried out using FORTRAN 77 language. Figure 2 shows the flow chart for the computer code, which was developed in a simple user – friendly and interactive form. The required input data are rolling speed, furnace temperature, initial and final height of the specimen, and specimen width. From the output of the program the mean temperature, the temperature distribution across the thickness of the material and the core temperature of the rolled specimen at different specimen geometries will be revealed.

Program Validation

The hot rolling experiment performed on HCSS316 provided a data base for assessment of the validity of the simulated model. Table I shows the chemical composition and results of the preliminary metallographic tests on the material. The computer program was executed using experimental values presented in Table II. A total of sixteen different specimens were tested and these cover the specimen schedule shown in Table III.

RESULTS AND DISCUSSION

The Output of the FORTRAN code, run with an IBM compatible Pentium (r) Processor, is presented in Tables IV-XIX. Each of the tables shows temperature data for HCSS316 specimen with different geometrical forms. The geometric variations are quantified by the width / height ratio evaluated as geometric factor, for each specimen, as computed in the tables. Other output data include the mid-thickness (core) temperature and local temperature values at seventeen zones across the material's thickness. A comparison of the simulated mean rolling temperature and specimen's core temperature with experimental values is presented in Fig. 3. The temperature distribution in tables IV-XIX is graphically illustrated in Fig. 4 – Fig. 8.

From the tables, a pattern of variation in temperature across the specimen's thickness is evident. This is in agreement with works of Aiyedun, (1984) using the Bland and Ford's Theory (BF) and Shobowale, (1998) where Sim's theory was adopted. During rolling, temperature changes continuously, due to heat losses to the environment, to the rolls and heat generated by deformation. The validity of the present simulation is further confirmed by the agreement between simulated (core and mean rolling temperature) results and experimental values earlier obtained by Aiyedun, (1984) as seen in Fig. 3; the maximum deviation being 2.537% for specimen H51. Core temperature characteristics of HCSS316 have been reported on by Ojediran and Alamu, (2002)

From the specimen schedule (Table III), the HCSS316 slabs designated as H50, H51, H52 and H53 have different geometries and were rolled at low strain rates (≅0.09s^{-1}) (v = 9.32mms^{-1}) with large diameter rolls (254.0mm). Fig. 4 showed no variation in the temperature distribution pattern for these Specimens. The pattern of a gradual temperature increase from the rolling surfaces to the specimen core remained consistent at different geometrical factors investigated.

Similarly, Specimens H54, H55, H56 and H57 rolled at higher speed (133mms^{-1}), i.e. higher strain rate (≥1.24 s^{-1}), with the same mill roll diameter (254.0mm) and reduction (≅10%), and with different geometry, described sets of curves that are almost super-imposing (Fig. 5). The foregoing, on the one hand, suggests that geometry of HCSS316 ingot does not have appreciable effect on the temperature distribution pattern in the material during hot rolling; on the other hand, the material geometry appeared to be independent of the speed of rolling and, hence, the strain rates.

Table I: Chemical Compositions and Preliminary Metallographic Data of HCSS316 Aiyedun, (1984,1986)

Element in HCSS316	Percentage Composition (%wt)	Preliminary Measurement	Value
C	0.054	Mean Grain Size,	
S	0.016	(μm)	39.30
Mo	2.050	Aspect Ratio	1.02
Ni	11.300	Micro hardness HV	
Si	0.540	(kg/mm^2)	165.00
Cr	17.400	Temperature,	
W	<0.020	(^{O}C)	20.00
Mn	1.370	0.2% P.S.	
Nb	0.100	(N/mm^2)	246.00
V	0.070	Ultimate Tensile Strength,	
Ti	0.040	(N/mm^2)	595.00
Co	0.140	Elongation,	
Cu	0.320	(%)	67.00
N	524ppm	Reduction in Area,	
O	122ppm	(%)	66.00

TABLE II: The Reverse Sandwich Rolling Experimental Results (Aiyedun, 1984)

S/N	SPECIMEN NO.	FURNACE TEMPERATURE (^{O}C)	THICKNESS INITIAL (mm)	THICKNESS FINLAL (mm)	WIDTH (mm)	ROLLING SPEED (mm/s)	TEMPERATURE MEAN (^{O}C)	TEMPERATURE CORE (^{O}C)	STRAIN RATE (s^{-1})
			Mill A (Roll Diameter = 254.0mm)						
1	H50	1120	14.17	12.73	75.17	009.32	910.0	1035.0	0.08
2	H51	1128	12.03	10.82	75.20	009.32	927.0	1050.0	0.09
3	H52	1123	10.04	09.09	75.20	009.32	888.0	1010.0	0.09
4	H53	1122	08.03	07.40	75.23	009.32	887.0	999.0	0.09
5	H54	1122	14.09	12.56	75.17	133.00	1038.0	1070.0	1.24
6	H55	1123	12.03	10.70	74.83	133.00	1029.0	1065.0	1.35
7	H56	1125	09.46	08.49	74.80	133.00	1026.0	1068.0	1.45
8	H57	1126	07.81	06.86	74.80	133.00	1032.0	1030.0	1.74
			Mill B (Roll Diameter = 139.7mm)						
9	P58	1142	14.02	12.51	75.00	021.01	1002.0	1070.0	0.25
10	P59	1134	12.10	10.80	75.01	018.06	978.0	1050.0	0.24
11	P60	1121	10.02	08.92	74.09	017.04	948.0	1035.0	0.25
12	P61	1124	07.83	07.02	75.02	017.03	960.0	1020.0	0.26
13	P62	1124	13.93	12.45	75.01	156.07	1043.0	1080.0	1.84
14	P63	1122	12.03	10.76	75.00	156.07	1032.0	1060.0	1.98
15	P64	1118	10.19	09.10	75.00	159.00	1025.0	1055.0	2.19
16	P65	1128	08.14	07.33	74.09	156.07	1036.0	1065.0	2.31

Table III: Hot Rolling Specimen Schedule

NATURE OF SPECIMEN		ROLLING PARAMETERS
Specimen	**Geometry Factor (w/h_1)**	Low rolling speed: (9.32mms^{-1})
H50	5.30	Low strain rates: (0.08,0.09,0.09,0.09)s^{-1}
H51	6.25	High roll diameter: (254.0mm)
H52	8.27	Low reduction: (≅10%)
H53	9.37	Furnace Temperature: (≅invariant)
Specimen	**Geometry Factor (w/h_1)**	High rolling speed: (133mms^{-1})
H54	5.33	High strain rates: (1.24,1.35,1.45,1.74)s^{-1}
H55	6.22	High roll diameter: (254.0mm)
H56	7.91	Low reduction: (≅10%)
H57	9.58	Furnace Temperature: (≅invariant)
Specimen	**Geometry Factor (w/h_1)**	Low rolling speed: (≤21.01mms^{-1})
P58	5.35	Low strain rates: (0.25,0.24,0.25,0.26)s^{-1}
P59	6.25	Low roll diameter: (139.70mm)
P60	7.39	Low reduction: (≅10%)
P61	9.58	Furnace Temperature: (≅invariant)
Specimen	**Geometry Factor (w/h_1)**	High rolling speed: (≅156.07mms^{-1})
P62	5.38	High strain rates: (1.84,1.98,2.19,2.31)s^{-1}
P63	6.23	Low roll diameter: (139.70mm)
P64	7.36	Low reduction: (≅10%)
P65	9.26	Furnace Temperature: (≅invariant)

However, as seen in Fig. 8, the temperature distribution curves differ in gradient for rolling at low and high strain rates. Detailed review of this observation abounds in literatures (Aiyedun and Sellars, 1998; Shoboowale, 1998; Alamu, 2002; Alamu and Aiyedun, 2003). At low rolling speed (low strain rate) the roll contact time increases, hence heat transfer to the environment and the roll increases significantly, leading to a large mean temperature drop in the material. This results in a high temperature gradient, which penetrates deep into the material's thickness. Conversely, at high strain rates, the contact time is greatly reduced, thus the temperature drop is comparatively minimal, and occurs predominantly at regions close to the rolling surfaces (Alamu and Taiwo, 2002; Alamu and Durowoju, 2003). The contact time phenomenon forms the basis of a higher strength surface cladding a lower strength matrix, referred to as 'the reverse sandwich effect' by Aiyedun, (1984).

Fig. 6 and Fig. 7 reveal a similar inference to that drawn from Fig. 4 and Fig. 5. Specimen P58, P59, P60 and P61 rolled at low strain rates (≅0.25s^{-1}), ≅10% reduction and 139.7mm roll diameter have identical temperature distribution pattern, variation in the individual geometries notwithstanding (Fig. 6). Also, specimen P62, P63, P64 and P65, with different geometric factors, as revealed in Fig.7, showed no significant variation in their respective temperature distribution pattern. Besides, the similarity of Fig. 4 and Fig. 6 and of Fig.5 and Fig. 7 implies that temperature distribution pattern is independent of the roll diameter and specimen geometry.

CONCLUSION

It is concluded that the temperature distribution pattern in HCSS316 does not have appreciable effect on the geometry of the in-going strip, slab or billet during hot rolling at low and high strain rates, low reductions (≤10%), furnace temperature of about 1125^{O}C and geometric factor (width-to-height ratio) range of 5.3 – 9.6.

```
C*********************************************************
C     HOT ROLLING TEMPERATURE DISTRIBUTION PROGRAM
C     Written by :   O. J. ALAMU & P. O. Aiyedun
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(*,*)'Supply the Width of the Specimen.'
      READ(*,*)W
      WRITE(7,*)
      WRITE(7,*)
      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

C  COMPUTATION OF GEOMETRICAL FACTOR
      GF = W/HO

   13 CONTINUE
   25 FORMAT(A14)
   26 FORMAT(1X,'SPECIMEN NO.  =  'A4,/1X,'GEOMETRICAL FACTOR = 'F5.2)
   27 FORMAT(1X,'MEAN TEMPERATURE =          'F7.2)
   32 FORMAT(1X,'CORE TEMPERATURE =          'F7.2)
   28 FORMAT(1X,I2,6X,F5.2,6X,F8.2)
      WRITE(7,26)SPNO,GF
      WRITE(7,27)TMEAN
      WRITE(7,32)T(9)
      WRITE(7,*)'_______________________________________________'
      WRITE(7,*)'S/N          HEIGHT(mm)          TEMPERATURE'
      WRITE(7,*)'        ACROSS THICKNESS     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
```

TABLE (IV - XIX): Output of the Temperature Distribution Simulation

Table IV

SPECIMEN NO.	=	H50
GEOMETRICAL FACTOR	=	5.30
MEAN TEMPERATURE	=	912.20
CORE TEMPERATURE	=	1016.10

S/N	HEIGHT (mm) ACROSS THICKNESS	TEMPERATURE DISTRIBUTION
1	.00	704.40
2	.83	766.74
3	1.83	829.08
4	2.83	891.42
5	3.83	953.76
6	4.83	966.23
7	5.83	978.70
8	6.83	991.16
9	7.09	1016.10
10	8.09	991.16
11	9.09	978.70
12	10.09	966.23
13	11.09	953.76
14	12.09	891.42
15	13.09	829.08
16	14.09	766.74
17	14.17	704.40

Table VI

SPECIMEN NO.	=	H52
GEOMETRICAL FACTOR	=	8.27
MEAN TEMPERATURE	=	914.64
CORE TEMPERATURE	=	1018.82

S/N	HEIGHT (mm) ACROSS THICKNESS	TEMPERATURE DISTRIBUTION
1	.00	706.29
2	.59	768.80
3	1.59	831.30
4	2.59	893.81
5	3.59	956.32
6	4.59	968.82
7	5.59	981.32
8	6.59	993.82
9	5.02	1018.82
10	6.02	993.82
11	7.02	981.32
12	8.02	968.82
13	9.02	956.32
14	10.02	893.81
15	11.02	831.30
16	12.02	768.80
17	10.04	706.29

Table V

SPECIMEN NO.	=	H51
GEOMETRICAL FACTOR	=	6.25
MEAN TEMPERATURE	=	918.72
CORE TEMPERATURE	=	1023.36

S/N	HEIGHT (mm) ACROSS THICKNESS	TEMPERATURE DISTRIBUTION
1	.00	709.43
2	.71	772.22
3	1.71	835.00
4	2.71	897.79
5	3.71	960.57
6	4.71	973.13
7	5.71	985.69
8	6.71	998.24
9	6.02	1023.36
10	7.02	998.24
11	8.02	985.69
12	9.02	973.13
13	10.02	960.57
14	11.02	897.79
15	12.02	835.00
16	13.02	772.22
17	12.03	709.43

Table VII

SPECIMEN NO.	=	H53
GEOMETRICAL FACTOR	=	9.37
MEAN TEMPERATURE	=	913.83
CORE TEMPERATURE	=	1017.92

S/N	HEIGHT (mm) ACROSS THICKNESS	TEMPERATURE DISTRIBUTION
1	.00	705.66
2	.47	768.11
3	1.47	830.56
4	2.47	893.01
5	3.47	955.46
6	4.47	967.95
7	5.47	980.44
8	6.47	992.93
9	4.02	1017.92
10	5.02	992.93
11	6.02	980.44
12	7.02	967.95
13	8.02	955.46
14	9.02	893.01
15	10.02	830.56
16	11.02	768.11
17	8.03	705.66

Table VIII

SPECIMEN NO. = H54
GEOMETRICAL FACTOR = 5.33
MEAN TEMPERATURE = 1044.62
CORE TEMPERATURE = 1083.31

S/N	HEIGHT (mm) ACROSS THICKNESS	TEMPERATURE DISTRIBUTION
1	.00	967.24
2	.83	990.46
3	1.83	1013.67
4	2.83	1036.88
5	3.83	1060.10
6	4.83	1064.74
7	5.83	1069.38
8	6.83	1074.02
9	7.05	1083.31
10	8.05	1074.02
11	9.05	1069.38
12	10.05	1064.74
13	11.05	1060.10
14	12.05	1036.88
15	13.05	1013.67
16	14.05	990.46
17	14.09	967.24

Table X

SPECIMEN NO. = H56
GEOMETRICAL FACTOR = 7.91
MEAN TEMPERATURE = 1047.41
CORE TEMPERATURE = 1086.21

S/N	HEIGHT (mm) ACROSS THICKNESS	TEMPERATURE DISTRIBUTION
1	.00	969.83
2	.56	993.10
3	1.56	1016.38
4	2.56	1039.66
5	3.56	1062.93
6	4.56	1067.59
7	5.56	1072.24
8	6.56	1076.90
9	4.73	1086.21
10	5.73	1076.90
11	6.73	1072.24
12	7.73	1067.59
13	8.73	1062.93
14	9.73	1039.66
15	10.73	1016.38
16	11.73	993.10
17	9.46	969.83

Table IX

SPECIMEN NO. = H55
GEOMETRICAL FACTOR = 6.22
MEAN TEMPERATURE = 1045.55
CORE TEMPERATURE = 1084.28

S/N	HEIGHT (mm) ACROSS THICKNESS	TEMPERATURE DISTRIBUTION
1	.00	968.10
2	.71	991.34
3	1.71	1014.57
4	2.71	1037.81
5	3.71	1061.04
6	4.71	1065.69
7	5.71	1070.34
8	6.71	1074.98
9	6.02	1084.28
10	7.02	1074.98
11	8.02	1070.34
12	9.02	1065.69
13	10.02	1061.04
14	11.02	1037.81
15	12.02	1014.57
16	13.02	991.34
17	12.03	968.10

Table XI

SPECIMEN NO. = H57
GEOMETRICAL FACTOR = 9.58
MEAN TEMPERATURE = 1048.34
CORE TEMPERATURE = 1087.17

S/N	HEIGHT (mm) ACROSS THICKNESS	TEMPERATURE DISTRIBUTION
1	.00	970.69
2	.46	993.99
3	1.46	1017.28
4	2.46	1040.58
5	3.46	1063.88
6	4.46	1068.54
7	5.46	1073.19
8	6.46	1077.85
9	3.91	1087.17
10	4.90	1077.85
11	5.90	1073.19
12	6.90	1068.54
13	7.90	1063.88
14	8.90	1040.58
15	9.90	1017.28
16	10.91	993.99
17	7.81	970.69

Table XII

SPECIMEN NO.	=	P58
GEOMETRICAL FACTOR	=	5.35
MEAN TEMPERATURE		978.86
CORE TEMPERATURE	=	1060.43

S/N	HEIGHT (mm) ACROSS THICKNESS	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

Table XIII

SPECIMEN NO.	=	P59
GEOMETRICAL FACTOR	=	6.25
MEAN TEMPERATURE	=	972.00
CORE TEMPERATURE	=	1053.00

S/N	HEIGHT (mm) ACROSS THICKNESS	TEMPERATURE DISTRIBUTION
1	.00	810.00
2	.71	858.60
3	1.71	907.20
4	2.71	955.80
5	3.71	1004.40
6	4.71	1014.12
7	5.71	1023.84
8	6.71	1033.56
9	6.05	1053.00
10	7.05	1033.56
11	8.05	1023.84
12	9.05	1014.12
13	10.05	1004.40
14	11.05	955.80
15	12.05	907.20
16	13.05	858.60
17	12.10	810.00

Table XIV

SPECIMEN NO.	=	P60
GEOMETRICAL FACTOR	=	7.39
MEAN TEMPERATURE	=	960.86
CORE TEMPERATURE	=	1040.93

S/N	HEIGHT (mm) ACROSS THICKNESS	TEMPERATURE DISTRIBUTION
1	.00	800.71
2	.59	848.76
3	1.59	896.80
4	2.59	944.84
5	3.59	992.89
6	4.59	1002.49
7	5.59	1012.10
8	6.59	1021.71
9	5.01	1040.93
10	6.01	1021.71
11	7.01	1012.10
12	8.01	1002.49
13	9.01	992.89
14	10.01	944.84
15	11.01	896.80
16	12.01	848.76
17	10.02	800.71

Table XV

SPECIMEN NO.	=	P61
GEOMETRICAL FACTOR	=	9.58
MEAN TEMPERATURE	=	963.43
CORE TEMPERATURE	=	1043.71

S/N	HEIGHT (mm) ACROSS THICKNESS	TEMPERATURE DISTRIBUTION
1	.00	802.86
2	.46	851.03
3	1.46	899.20
4	2.46	947.37
5	3.46	995.54
6	4.46	1005.18
7	5.46	1014.81
8	6.46	1024.45
9	3.92	1043.71
10	4.92	1024.45
11	5.92	1014.81
12	6.92	1005.18
13	7.92	995.54
14	8.91	947.37
15	9.91	899.20
16	10.92	851.03
17	7.83	802.86

Table XVI

SPECIMEN NO.	=	P62
GEOMETRICAL FACTOR	=	5.38
MEAN TEMPERATURE	=	1046.48
CORE TEMPERATURE	=	1085.24

S/N	HEIGHT (mm) ACROSS THICKNESS	TEMPERATURE DISTRIBUTION
1	.00	968.97
2	.82	992.22
3	1.82	1015.48
4	2.82	1038.73
5	3.82	1061.99
6	4.82	1066.64
7	5.82	1071.29
8	6.82	1075.94
9	6.97	1085.24
10	7.97	1075.94
11	8.97	1071.29
12	9.97	1066.64
13	10.97	1061.99
14	11.97	1038.73
15	12.97	1015.48
16	13.97	992.22
17	13.93	968.97

Table XVII

SPECIMEN NO.	=	P63
GEOMETRICAL FACTOR	=	6.23
MEAN TEMPERATURE	=	1044.62
CORE TEMPERATURE	=	1083.31

S/N	HEIGHT (mm) ACROSS THICKNESS	TEMPERATURE DISTRIBUTION
1	.00	967.24
2	.71	990.46
3	1.71	1013.67
4	2.71	1036.88
5	3.71	1060.10
6	4.71	1064.74
7	5.71	1069.38
8	6.71	1074.02
9	6.02	1083.31
10	7.02	1074.02
11	8.02	1069.38
12	9.02	1064.74
13	10.02	1060.10
14	11.02	1036.88
15	12.02	1013.67
16	13.02	990.46
17	12.03	967.24

Table XVIII

SPECIMEN NO.	=	P64
GEOMETRICAL FACTOR	=	7.36
MEAN TEMPERATURE	=	1040.90
CORE TEMPERATURE	=	1079.45

S/N	HEIGHT (mm) ACROSS THICKNESS	TEMPERATURE DISTRIBUTION
1	.00	963.79
2	.60	986.92
3	1.60	1010.06
4	2.60	1033.19
5	3.60	1056.32
6	4.60	1060.94
7	5.60	1065.57
8	6.60	1070.20
9	5.10	1079.45
10	6.10	1070.20
11	7.10	1065.57
12	8.09	1060.94
13	9.09	1056.32
14	10.10	1033.19
15	11.10	1010.06
16	12.10	986.92
17	10.19	963.79

Table XIX

SPECIMEN NO.	=	P65
GEOMETRICAL FACTOR	=	9.26
MEAN TEMPERATURE	=	1050.21
CORE TEMPERATURE	=	1089.10

S/N	HEIGHT (mm) ACROSS THICKNESS	TEMPERATURE DISTRIBUTION
1	.00	972.41
2	.48	995.75
3	1.48	1019.09
4	2.48	1042.43
5	3.48	1065.77
6	4.48	1070.43
7	5.48	1075.10
8	6.48	1079.77
9	4.07	1089.10
10	5.07	1079.77
11	6.07	1075.10
12	7.07	1070.43
13	8.07	1065.77
14	9.07	1042.43
15	10.07	1019.09
16	11.07	995.75
17	8.14	972.41

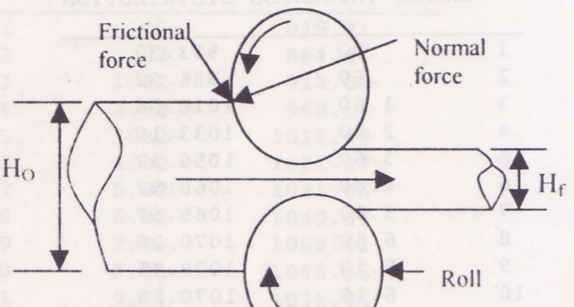

FIG. 1 (a) Normal Rolling Process

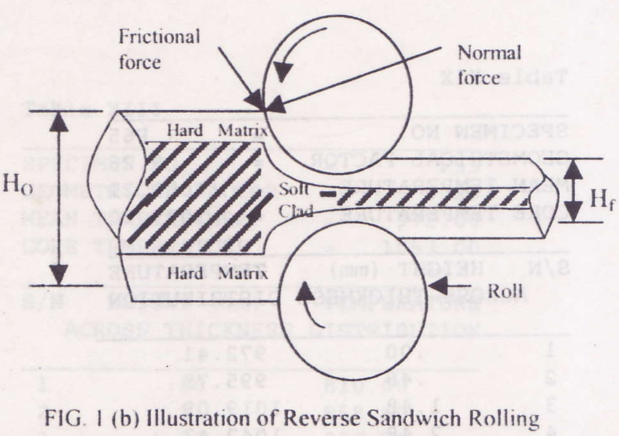

FIG. 1 (b) Illustration of Reverse Sandwich Rolling

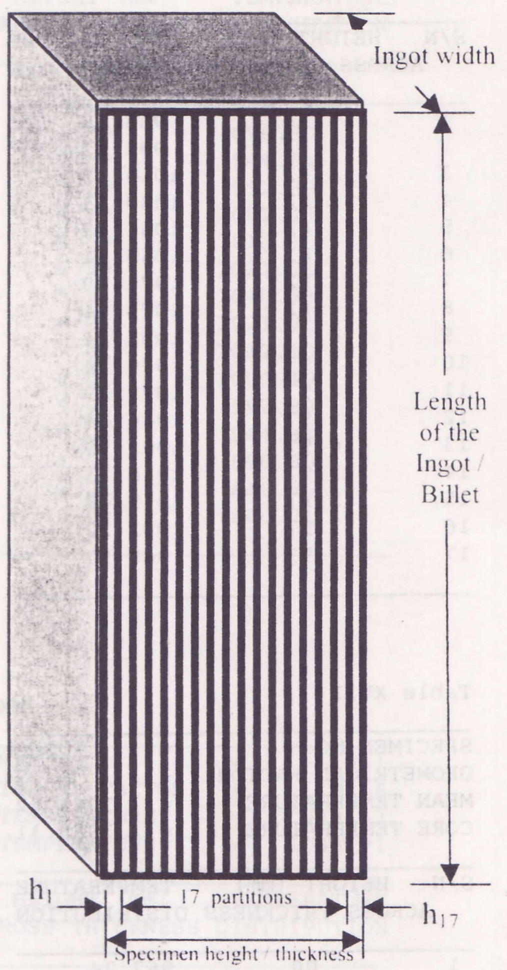

FIG. 1(c): A sketch of the rolling specimen partitioned into 17 zones

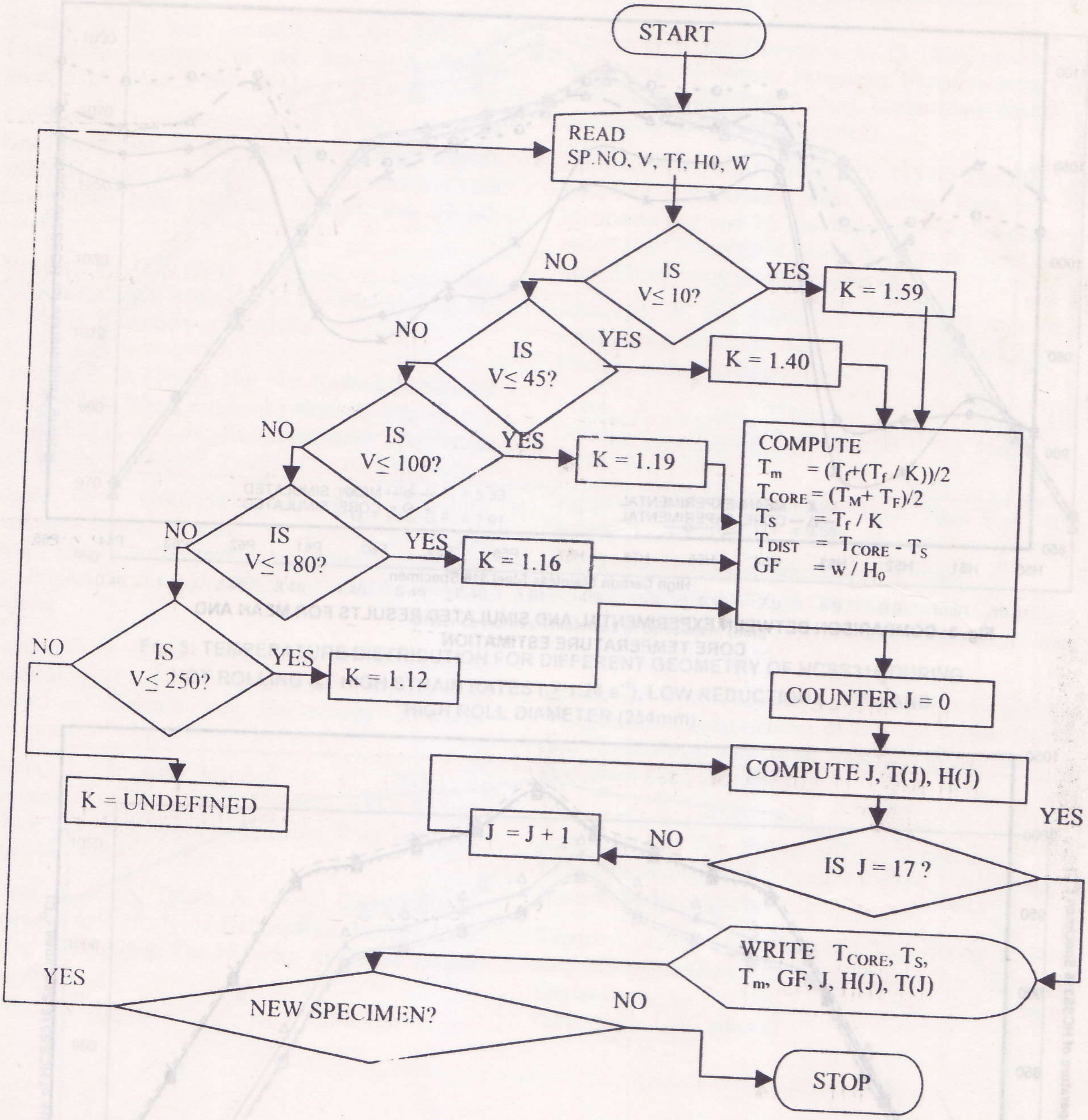

Fig. 2: Flow Chart for the Simulation

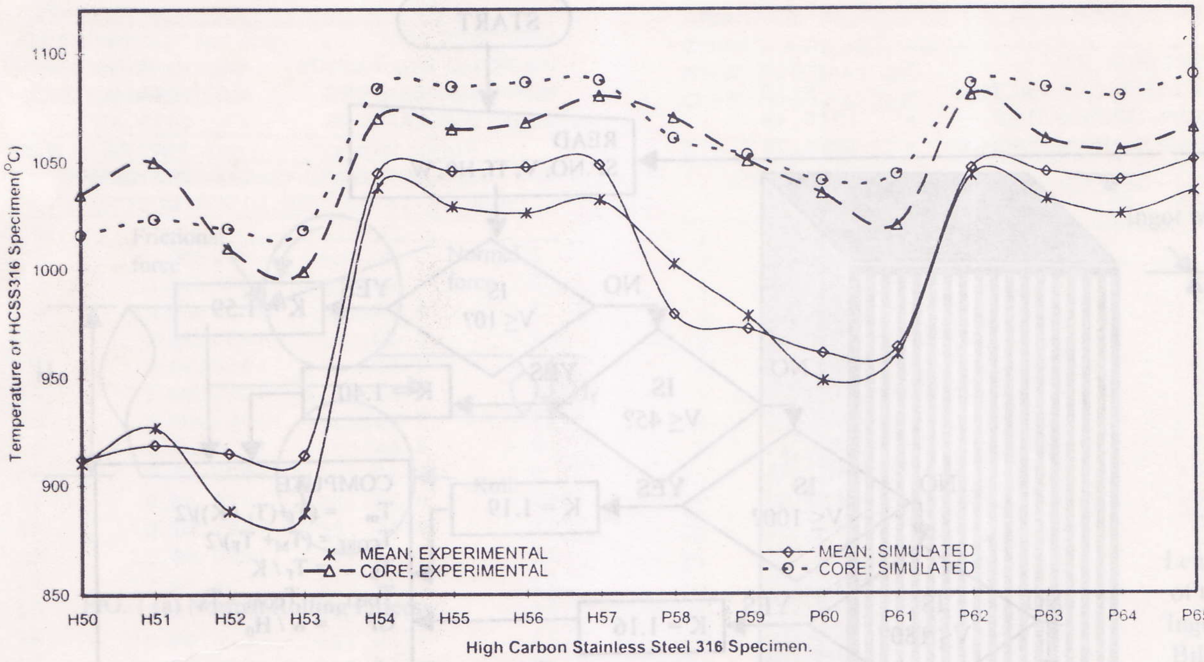

Fig. 3: COMPARISON BETWEEN EXPERIMENTAL AND SIMULATED RESULTS FOR MEAN AND CORE TEMPERATURE ESTIMATION

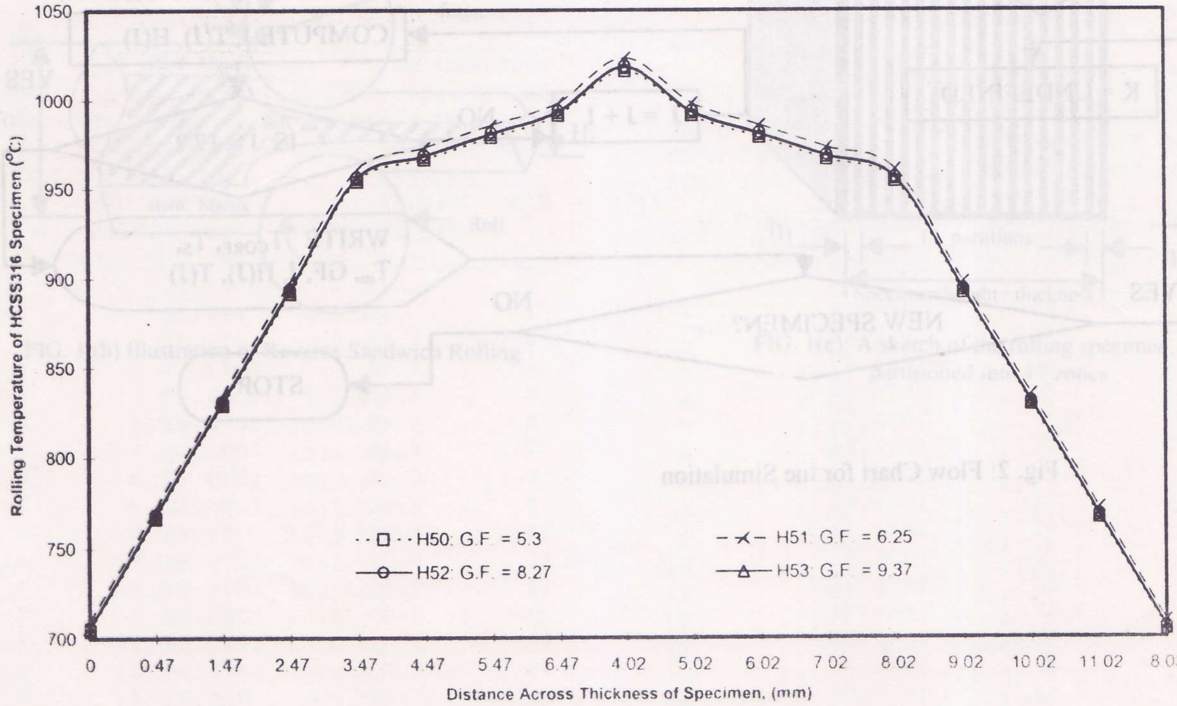

Fig. 4: TEMPERATURE DISTRIBUTION FOR DIFFERENT GEOMETRY OF HCSS316 DURING HOT ROLLING AT LOW STRAIN RATES ($\simeq$ 0.09 s^{-1}), LOW REDUCTION ($\simeq$10%) AND HIGH ROLL DIAMETER (254mm).

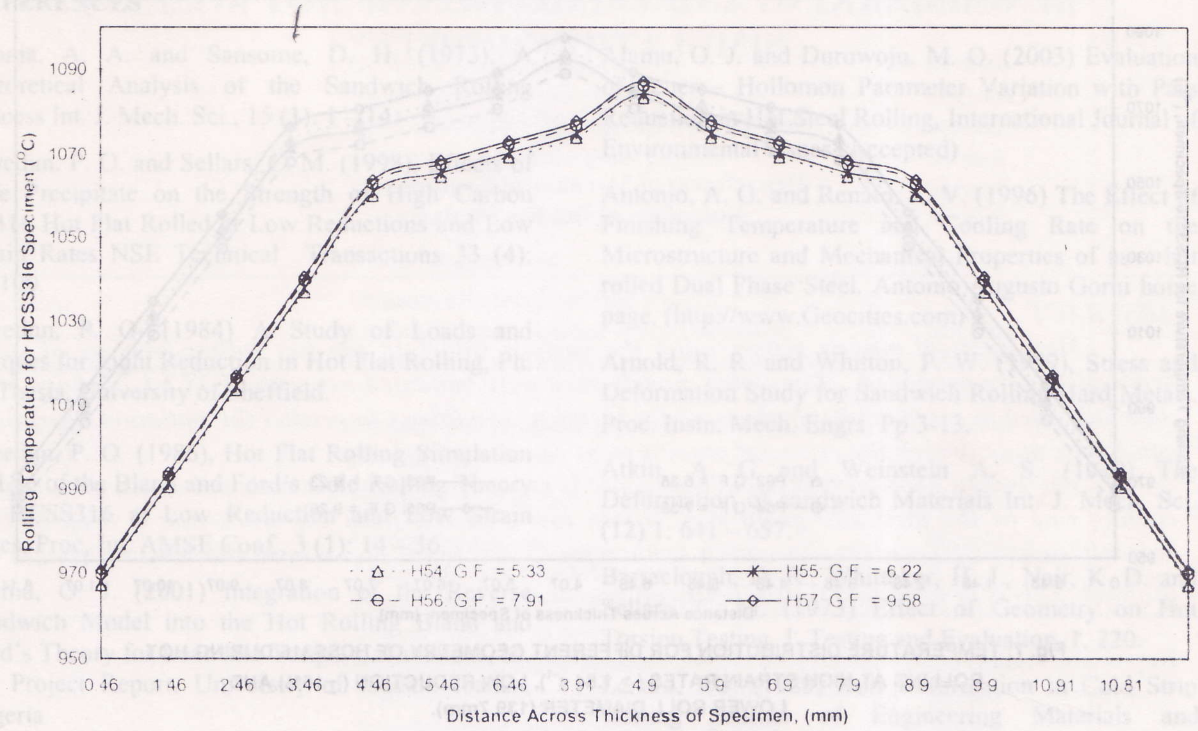

Fig. 5: TEMPERATURE DISTRIBUTION FOR DIFFERENT GEOMETRY OF HCSS316 DURING HOT ROLLING AT HIGH STRAIN RATES ($\geq 1.24\ s^{-1}$), LOW REDUCTION (~10%) AND HIGH ROLL DIAMETER (254mm).

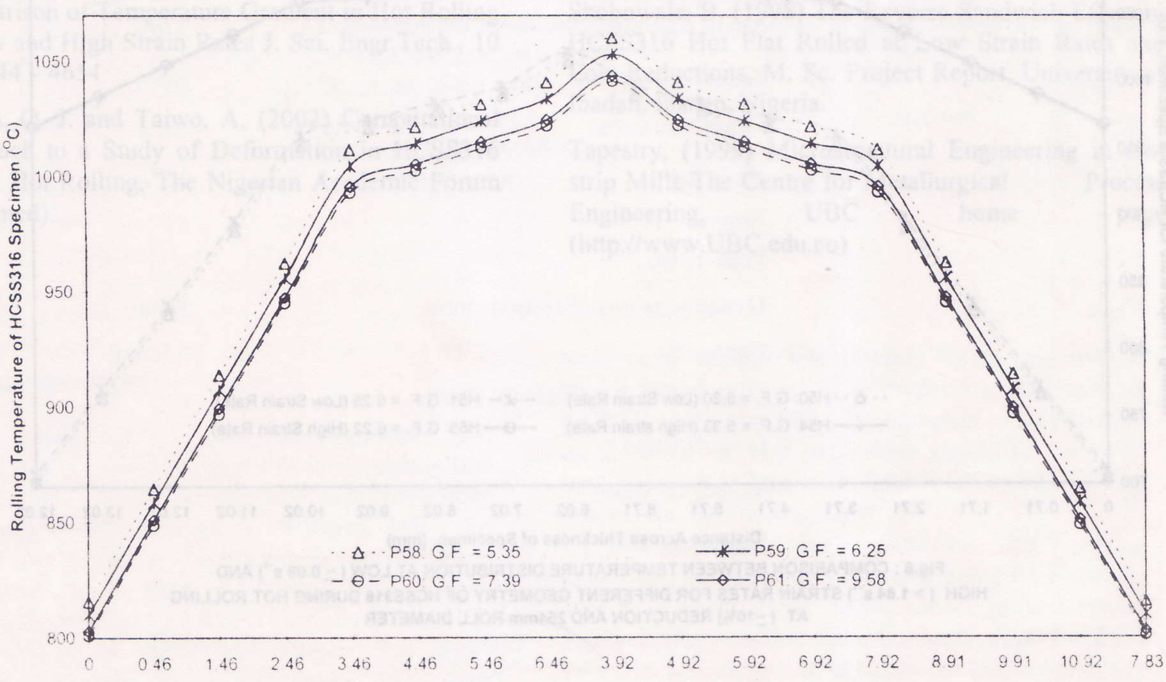

Fig. 6: TEMPERATURE DISTRIBUTION FOR DIFFERENT GEOMETRY OF HCSS316 DURING HOT ROLLING AT LOW STRAIN RATES ($\leq 0.26\ s^{-1}$), LOW REDUCTION (~10%) AND LOWER ROLL DIAMETER (139.7mm).

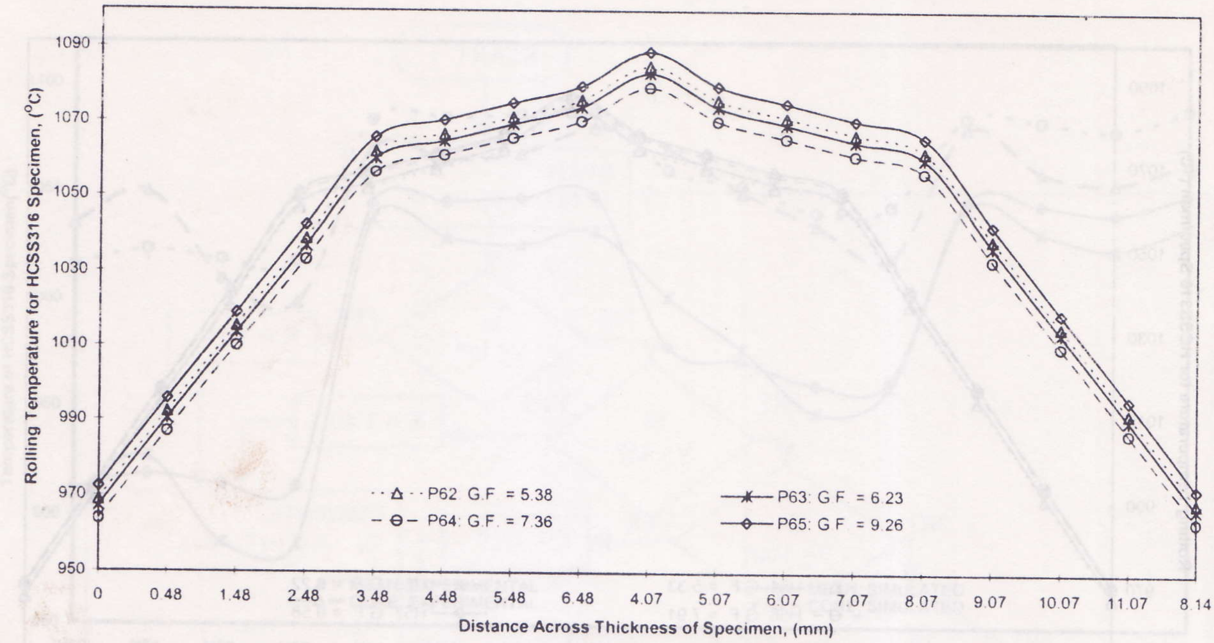

Fig. 7: TEMPERATURE DISTRIBUTION FOR DIFFERENT GEOMETRY OF HCSS316 DURING HOT ROLLING AT HIGH STRAIN RATES (≥ 1.84 s^{-1}), LOW REDUCTION (~10%) AND LOWER ROLL DIAMETER (139.7mm).

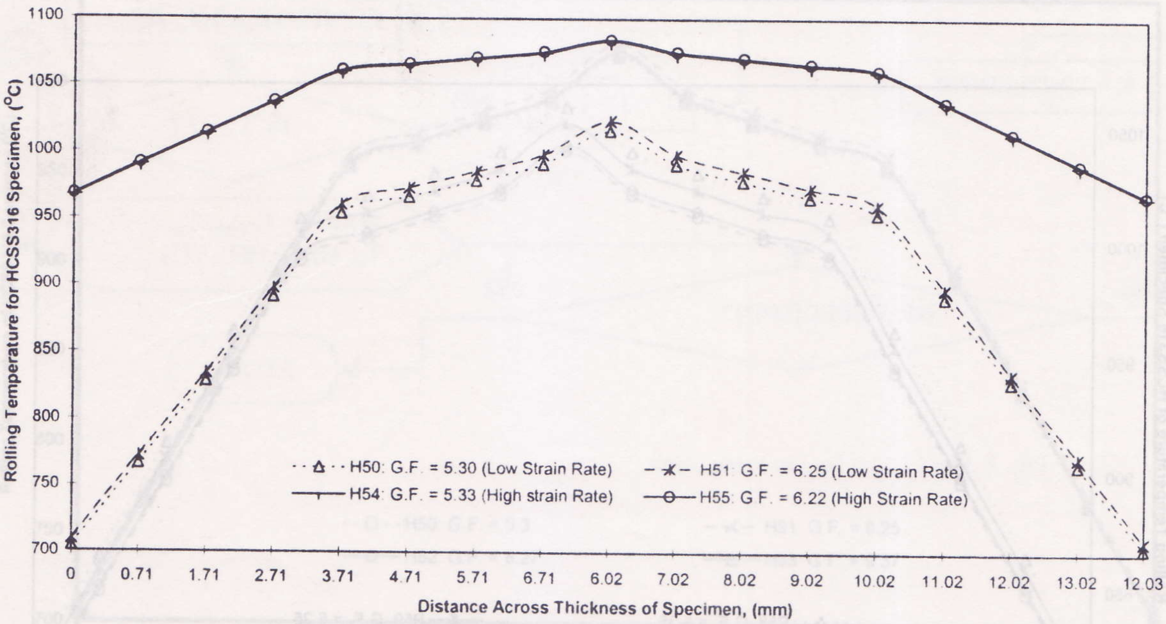

Fig.8 : COMPARISON BETWEEN TEMPERATURE DISTRIBUTION AT LOW (~ 0.09 s^{-1}) AND HIGH (> 1.84 s^{-1}) STRAIN RATES FOR DIFFERENT GEOMETRY OF HCSS316 DURING HOT ROLLING AT (~10%) REDUCTION AND 254mm ROLL DIAMETER .

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