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A Study of Zenner – Holomon Parameter Variation with Pass Reduction in Steel Rolling

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ABRSTRACT **:** An attempt is made in this work to establish mathematical relationships between the Zener – Hollomon Parameter and rolling reduction per pass in the hot rolling of Type 316 High Carbon Stainless Steel (HCSS316). The hot rolling simulation of steel based on the Reverse Sandwich Model and that based on the Sims' theory were used with the hot rolling experimental data for HCSS316, to generate results which reveal the dependency of the two rolling parameters on each other. These results were then processed with the EXCEL Package to arrive at a quantitative description of the observed relationship. The Zener–Hollomon parameter (Z) was found to be a non linear function of rolling reduction (r): ($Log_{10}(Z) = ar^3 + br^2 + cr + d; ...... a,b,c,d = constants$) for High Carbon Stainless Steel hot flat rolled at low strain rates. The results compare favourably with experimental inferences.

KEY WORD: *Zener-Hollomon Parameter, rolling reduction, simulation*]

I. INTRODUCTION

Rolling nowadays accounts for about 90% of all metals produced by metal working processes. It was first developed in the late 1500s. Traditionally, the initial material form for rolling was an ingot. By far the largest amount of finished steel production is achieved by rolling. The Semi-finished products cast from the steelmaking furnace are reheated to the austenising range and passed through a series of mills with rolls of the required profile to force the hot steel into the finished shape. (Graham, 1993) Developed in the mid – 1800s two high and three high rolling mills are still used today for initial breakdown passes on cast ingots. However, this practice is now being rapidly replaced by continuous casting and rolling, with much higher efficiency and lower cost.The advent of continuous casters has necessitated hot flat rolling at low strain rates (0.01 – 1.55) s^{-1} and low reduction (≅ 10%) (Aiyedun, 1986). Under such rolling condition, the contact time in the roll gap increases and heat loss from the pre-heated ingot to the surroundings and the rolls increases. This variation in temperature induces a non-uniform deformation pattern in the through-thickness of the rolled steel. The deformation, by virtue of the un-even re-crystallization and grain refinement, as a result creates in the material a low-temperature harder surface and a high-temperature softer core (Alamu and Aiyedun, 2003, Ojediran and Alamu, 2003).(see Fig.1)The prevailing situation has been investigated by authors. Barbosa, (1983), Leduc, (1983), and Aiyedun (1984) referred to the observed effect as "Reverse Sandwich" or Roll chilling, as the through-thickness hardness variation presents a direct opposite of what obtains in a sandwich rolling process, where harder metals are sandwiched between layers of softer metals to effect rolling of very hard and high strength metals into thin strips without rupture in the rolls (Afonja and Sansome, 1973).

Studies abound in literatures on deformation in sandwich rolling and the reverse sandwich effect or roll chilling. The adoption of computer simulation in modeling engineering systems further expands this area of study. The Zener-Hollomon parameter is uniquely related to stresses, and gives an indication of deformation in a material. Researchers (Zener and Hollomon, 1944; Aiyedun, 1984) have long established that deformation increases with decreasing Zener – Hollomon parameter value. Alamu and Taiwo, (2002) employed computer simulation to study deformation pattern in the hot rolling of High Carbon Stainless Steel type 316 (HCSSS316) using a reverse Sandwich Model developed by Shobowale (1998). In the work, the reverse sandwich model was simulated incorporating strain rate and Zener-Hollomon parameter computation for different zones along the thickness of HCSS316 during hot flat rolling, thus permitting a study of the deformation pattern of this material during hot rolling.In this work, the relationship between deformation rate, in terms of the Zener-Hollomon parameter and rolling reduction per pass in the hot rolling of HCSS316 is investigated, using the reverse sandwich model and Sims' theory of hot flat rolling, with hot flat rolling experimental data earlier obtained by researchers for HCSS316.

II. MATERIALS AND METHOD

Deformation in hot rolling is temperature dependent. In this process the strength of a metal decreases as temperature rises, and its grains can be distorted more easily. In line with Sims' theory, hot rolling process is characterized by "sticking throughout the roll gap" (Sims, 1954). However, this is not entirely true for hot rolling of HCSS316 at low strain rates; here, the rolling surfaces are sufficiently chilled leading to a mixed sliding –sticking condition in the roll gap (Aiyedun, 1986).

THEORIES OF METAL ROLLING

Lennard (1980), and Usamah and Lennard (1980), amongst other literatures have reported that, Orowan's theory is the most comprehensive among the many theories of rolling. According to Lennard, (1980), the approach requires mathematical descriptions of material behaviour and deformation as well as assumptions of frictional conditions at the roll – metal interface and mode of roll deformation. The complexity of the method of solution of Orowan's equation caused later researchers, notably, Sims, Bland and Ford, Alexander, Alexander and Ford and Atreya and Lennard to develop solutions based on simplifying assumptions.

1. <u>Orowan's Theory</u>*:*

According to Lennard, (1980) Orowan's theory can be summarized in the differential equation:

$$\frac{d}{d\phi}\left[h\left(s-2k\mp\tau\tan\phi\right)\right]=2R`\left(s.\sin\phi\pm\tau\cos\phi\right) \quad \text{……………..} \quad (1)$$

where: τ = interfacial shear stress,
s = roll pressure,
h = thickness of the strip in the roll gap,
k = yield strength in shear of the material,
R` = current radius of curvature of the roll at a particular location,
ϕ = independent variable (angle) measured from the centre line in the roll gap.

The instantaneous yield stress, k, depends on rolling temperature, strain and strain rate, and must be determined before evaluating the mean yield stress, $\overline{K}$, for subsequent computation of rolling parameters of interest such as load and torque.

2. <u>Sims' Theory of Hot Flat Rolling:</u>

According to Sims (1954), the only practicable method of allowing for the elastic deformation of the rolls is that due to Hitchcock, who replaced the actual distribution of pressure over the roll surface with an elliptical distribution giving the same total load. The roll, in its arc of contact with the material, is then of constant radius of curvature. Sims' hot flat rolling theory assumes a circular arc of contact, which is flattened in accordance with Hitchcok's formular:

$$R`=R_o\left(1+\frac{C.P}{\delta.W}\right) \quad \text{………………………………} \quad (2)$$

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,

$$C=8\frac{\left(1-v^2\right)}{\pi E} \quad \text{…………………………………} (3)$$

= 0.0223 mm^2 kN^{-1} for steel rolls, = 0.0247 mm^2 kN^{-1} for chilled C.I. rolls

also, P =132KN/ mm^2 (Sims, 1954; Aiyedun, 1984)

However, several authors have questioned the validity of this approach.

3. <u>The Bland and Ford's Theory:</u>

The Bland and Fords theory is basically a theory for cold rolling, where sliding takes place throughout the arc of contact but has been found applicable to hot rolling of HCSS316, where there is a mixed sticking - sliding condition (Aiyedun 1984). This is the situation for hot rolling of HCSS316 at (900 – 1200)^{o}C, (0 – 15) % reduction, (0.07 – 1.5) s^{-1} strain rates.

THE ROLL CHILLING EFFECT

A detailed description of the Reverse Sandwich Model based on the 'Roll Chilling Effect', which characterizes hot rolling of HCSS316 has been presented elsewhere; (Shobowale, (1998), Alamu, (2001), Alamu and Aiyedun, (2003)). The reverse sandwich rolling presents a situation whereby a high strength - metal clads a low strength metal. The strength variation being a direct consequence of drastic temperature changes during rolling. The reverse sandwich model predicts rolling temperatures, temperature distribution corresponding to different heights (17 Zones), the Zener-Hollomon parameter, yield stresses, rolling load and torque for HCSS316 rolled at low strain rates and low reduction.

DEFORMATION IN MATERIAL AND ROLLING TEMPERATURE

Extensive research work has been carried out on deformation modeling using the Zener-Hollomon parameter. A general drop in the Zener-Hollomon parameter from the rolling surfaces (lowest temperature zone) towards the core (temperature peak) of the material was observed by Alamu and Taiwo, (2002), implying that the material deforms increasingly towards the centre. The conclusion drawn was corroborated with the fact that metals deform at a greater rate at elevated temperatures (Early, 1977)

PASS REDUCTION AND THE ZENER – HOLLOMON PARAMETER

Reduction per pass during metal rolling process is given as:

$$\delta = H_f - H_o \qquad \text{……………………………………. (4)}$$

where; δ = rolling reduction, (mm),

H_f = final specimen thickness, (mm), H_o = initial specimen thickness, (mm).

Expressed as a percentage, we have:

$$r = \frac{H_f - H_o}{H_o} \times 100\% \qquad \text{…………………………………… (5)}$$

The Zener-Hollomon parameter was determined using the proposition of Zener and Hollomon, (1944):

$$\sigma = f\left(\varepsilon \times \exp\left(\frac{Q}{RT}\right)\right) = f(Z) \qquad \text{……………………. (6)}$$

where; ε = strain rate R = universal constant, (J /mol..K),

T = absolute temperature, (^{O}C) Z = Zener-Hollomon parameter.

Q = energy 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 HCSS316 at (900 – 1200)^{o}C, (0 – 15) % reduction, and (0.07 – 1.5) s^{-1} strain rates, Q = 460kJ / mol (Aiyedun, 1984).

III. MEAN STRAIN RATE

The resistance to deformation of hot metal is both strain and strain rate dependent. For this reason it is necessary to define the mean strain rate in the rolling pass.

According to Orowan and Pascal, mean strain rate is given as;

$$\dot{\varepsilon} = \frac{V_n}{\sqrt{Rh_1}}\sqrt{r}\left[\frac{1-\frac{3}{4}r}{1-r}\right] \qquad \text{…………………………(7)}$$

where; V_n = rolling velocity at the neutral position.

Ford and Alexander expressed it in the form:

$$\dot{\varepsilon} = \frac{V_n}{\sqrt{Rh_1}}\sqrt{r}\left[\frac{4-3r}{(2-r)^2}\right] \qquad \text{…………………..(8)}$$

The form of mean strain rate estimation adopted by Sims, R. B. is given as:

$$\dot{\varepsilon} = \frac{V_n}{\sqrt{Rh_1}}\frac{1}{\sqrt{r}}\ln\left[\frac{1}{1-r}\right] \qquad \text{……………………(9)}$$

Integration of equation (9) into equation (6) above gives the basis of Zener – Hollomon Parameter computation adopted by Sims. (Aiyedun, (1984)

According to Sellars, (1981) instantaneous strain rate in the roll gap is

$$\dot{\varepsilon} = 2v\frac{(h_1 - h_2)^{0.5}}{R^{0.5}h} \qquad \text{……………………(10)}$$

He further stated that the best mean strain rate will be one that gives a correct mean flow stress. Farag and Sellars, (1973) thus obtained an approximate empirical equation of the form:

$$\ddot{\varepsilon} = \frac{1.08V}{R^{0.5}\delta^{0.5}}\left(\frac{(\delta^2)^{(0.25)}}{h_1 h_2}\right)\left[\ln\frac{h_1}{h_2}\right]^{0.45} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(11)}$$

where:

δ = reduction V = peripheral velocity of rolls (mms^{-1})

The above equation due to Farag and Sellars was adopted in the Reverse Sandwich Model for computation of mean strain rate, which was then used in equation (6) to estimate the Zener - Hollomon Parameter (The quantity used to model deformation).

IV. MODEL SIMULATION AND VALIDATION

The computer code developed using FORTRAN 77 for Zener - Hollomon Parameter computation at different rolling reduction using the Reverse sandwich model is as provided. Fig. 2 shows the flow chart for the simulation. The Program is user friendly and interactive, accepting input manually from the screen and outputting results to user-defined file. Validation of the program was accomplished using data from hot rolling experimental work carried out by authors on HCSS316 using 2 high reversing laboratory rolling mills.

For the material under study, experimental data abound in literatures for hot rolling based on Sims' theory of hot flat rolling (Aiyedun, 1984; Shobowale, 1998; Alamu, 2001). The composition and thermo-mechanical history of the specimen is presented in Table I, while the input data for the simulation is as shown in Table II.

V. RESULTS AND DISCUSSION

The Output of the computer program, run with an IBM compatible Pentium (r) Processor, is presented in Tables III - VI. The tables show the Zener – Hollomon Parameter values corresponding to different rolling reduction characterized in different specimen. Also, the tables present the mean rolling temperature for each hot rolling schedule to enable further validation of the program via a comparison between simulated and experimental mean temperatures. This comparison is presented in Fig. 4. Similar data, from literatures, for hot flat rolling of HCSS316 adopting Sims' theory is presented in Table VII. These sets of data, processed with EXCEL package gave the polynomials shown in Fig. 3From the tables, variation of the Zener – Hollomon Parameter with rolling reduction is evident. This is in agreement with earlier works of authors (Shobowale, 1998; Alamu and Taiwo, 2002). In other words, the rate of deformation in HCSS316 during hot rolling is a function of the rolling reduction per pass. The possible relationship between these two parameters, as evident in Fig. 3, takes the form of a non-linear polynomial, and is consistent in the two approaches; the Reverse sandwich Model and Sims' theory.

From the two approaches investigated, the Zener – Hollomon Parameter as a function of rolling reduction takes the form: ($Log_{10}(Z) = ar^3 + br^2 + cr + d; ...... a, b, c, d = constants$). For Sims' theory, a = -0.1833, b = 1.45, c = -2.8667, d = 21; while for Reverse Sandwich Model; a = 0.1367, b = -1.28, c = 3.9833, and, d = 16.82.

Fig. 4 reveals an agreement between simulated mean temperature and experimental values. Similar comparisons have been used in other works (Shobowale, 1998; Alamu and Aiyedun, 2002, Ojediran and Alamu, 2002) to confirm the validity of the output of the computer program. Hence, results obtained compares favourably with experimental inferences as well as earlier works of researchers.

VI. CONCLUSION

In the hot rolling of HCSS316 at low strain rates, (0.01 – 1.55) s^{-1} and low reductions, (≅ 10%), the Zener – Hollomon Parameter, (Z), has been found to be dependent on rolling reduction, (r), per pass. For Sims' theory, $Log_{10}(Z) = -0.1833r^3 + 1.45r^2 - 2.8667r + 21$; while using the Reverse sandwich Model, $Log_{10}(Z) = 0.1367r^3 - 1.28r^2 + 3.9833r + 16.82$ for hot rolling computations.

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C-------------------------------------------------------------------
C  Program    :  HOT ROLLING DEFORMATION BASED ON RSM MODEL
C_______________________________________________________________________

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

Q=460000.0
GKR=8.314
P=132.0
C=0.02474
RO=139.70
AZEN = 0.0

C    FILES CREATION AND INTERACTIVE DATA ENTRY
     WRITE(*,*)'Enter a Filename for the Result.'
     READ(*,25)RSM
     OPEN(UNIT=7,FILE=RSM,STATUS='NEW')

10 WRITE(*,*)'Supply the Specimen Identification Number.'
READ(*,12)SPNO
```

```
WRITE(*,*)'Enter the Rolling Speed,(mm/s).'
READ(*,*)V
WRITE(*,*)'Supply the Furnace Temperature (Deg.Celcius).'
READ(*,*)TF
WRITE(*,*)'Supply the Initial Specimen Height,(mm).'
READ(*,*)HO
WRITE(*,*)'Enter the Final Specimen Height,(mm).'
READ(*,*)HF
WRITE(*,*) 'Enter the Width of the Specimen,(mm).'
READ(*,*) W

WRITE(7,*)
WRITE(7,100)SPNO
 100 FORMAT(1X,'OUTPUT FOR SPECIMEN 'A4)
WRITE(7,*)'------------------------------------------'

12 FORMAT(A4)
20 FORMAT(A1)
25 FORMAT(A4)

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
END IF
C    CALCULATION OF REDUCTION(DEL), PERCENTAGE REDUCTION(DELPER) AND
C    DEFORMED ROLL RADIUS(DR)

DEL = HO-HF
DELPER=((HO-HF)/HO)*100
DR = RO*(1+(C*P)/(DEL*W))

C    COMPUTATION OF MEAN TEMPERATURE(TMEAN),SURFACE TEMPERATURE(TE),
C    TEMPERATURE DISTRIBUTION(TDIST), MIDDLE TEMPERATURE(TMID) AND
C    TEMPERATURE VARIATION 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    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
C    ESTIMATION OF ZENER HOLLOMON PARAMETER ALONG THICKNESS
C    (Z1.........Z17)

DO 15 J = 1,17
PLOT(J) = ALOG10(SRT*DEXP(Q/(GKR*(T(J)+273))))
  15 CONTINUE


DO 35 J = 1,17
35 AZEN = AZEN+PLOT(J)
CONTINUE
AZEN = AZEN/17.0

26 FORMAT(1X,'SPECIMEN NO.                = 'A4)
27 FORMAT(1X,'MEAN TEMPERATURE,('C)        = 'F7.2)
37 FORMAT(1X,'ZENER-HOLLOMON PARAMETER(LOG) = 'F5.2)
40 FORMAT(1X,'ROLLING REDUCTION,(%)        = 'F5.2)

WRITE(7,26)SPNO
WRITE(7,27)TMEAN
WRITE(7,40)DELPER
WRITE(7,37)AZEN
WRITE(7,*)'_______________________________________________'
WRITE(*,29)RSM
29 FORMAT(1X,13HEnter,  edit  ,A14,14Hfor the output)
30 WRITE(*,*)'DO YOU WISH TO CONTINUE?(Y/N)'
READ(*,20)CONTD
IF(CONTD.EQ.IY) GO TO 10
IF(CONTD.EQ.IN) GO TO 31
WRITE(*,*)'INVALID RESPONSE !! ENTER (Y/N) USING UPPERCASE LETTER'
GO TO 30
  31 STOP
     END
```

Table I: Chemical Compositions and Thermo-mechanical Data for HCSS316

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 Data*.

S/N	SPEC. NO.	FURN. TEMP. (^{O}C)	THICKNESS INIT. (mm)	THICKNESS FINL. (mm)	WIDTH (mm)	ROLLING SPEED (mm/s)
1	H50	1120	14.17	12.73	75.17	009.32
2	H51	1128	12.03	10.82	75.20	009.32
3	H52	1123	10.04	09.09	75.20	009.32
4	H53	1122	08.03	07.40	75.23	009.32

*(Aiyedun,1984)

TABLE III:
OUTPUT FOR SPECIMEN H50

SPECIMEN NO. = H50
MEAN TEMPERATURE,('C) = 912.20
ROLLING REDUCTION,(%) = 10.16
ZENER-HOLLOMON PARAMETER(LOG) = 19.66

TABLE IV:
OUTPUT FOR SPECIMEN H51

SPECIMEN NO. = H51
MEAN TEMPERATURE,('C) = 918.72
ROLLING REDUCTION,(%) = 10.06
ZENER-HOLLOMON PARAMETER(LOG) = 20.76

TABLE V:
OUTPUT FOR SPECIMEN H52

SPECIMEN NO. = H52
MEAN TEMPERATURE,('C) = 914.64
ROLLING REDUCTION,(%) = 9.46
ZENER-HOLLOMON PARAMETER(LOG) = 20.94

TABLE VI:
OUTPUT FOR SPECIMEN H53

SPECIMEN NO. = H53
MEAN TEMPERATURE,('C) = 913.83
ROLLING REDUCTION,(%) = 7.85
ZENER-HOLLOMON PARAMETER(LOG) = 21.02

Table VII: *Values Obtained for the Specimens Using Sims' Theory.

S /N	Specimen Identification Number	Rolling Reduction (%)	$Log_{10}(Z)$
1	H50	10.16	19.40
2	H51	10.06	19.60
3	H52	9.46	20.50
4	H53	7.85	21.00

*Shobowale,(1998)

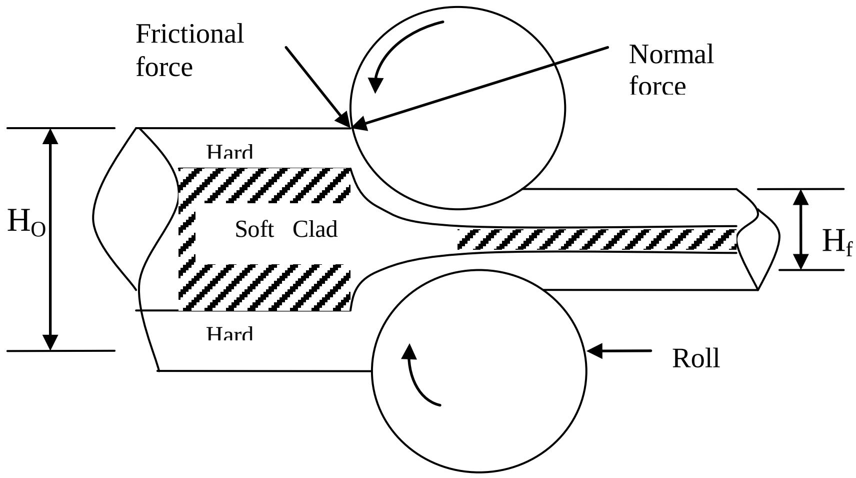

FIG. 1 Schematic Illustration of Reverse Sandwich Rolling Process.

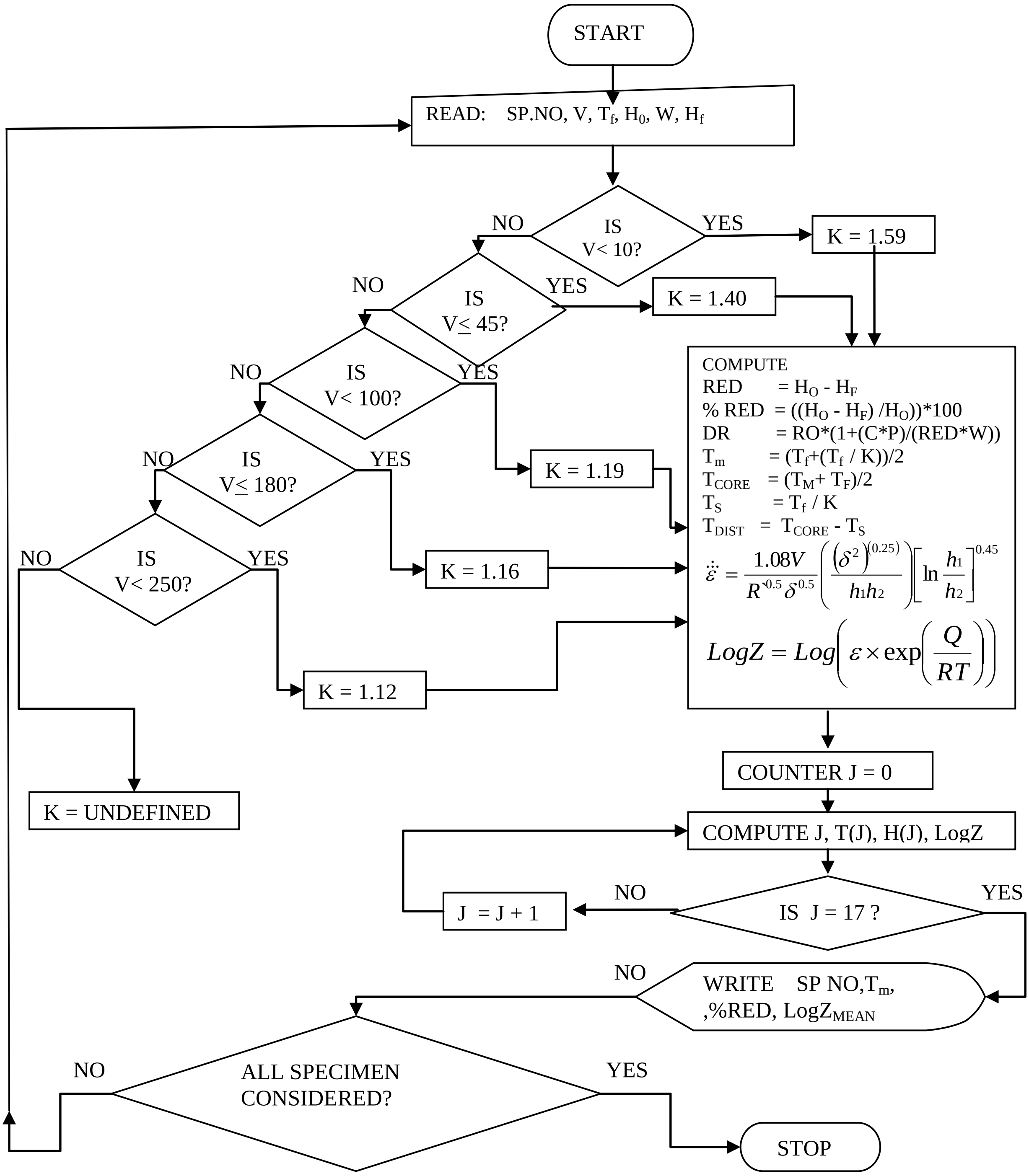

Fig. 2: Flow Chart for the RSM Simulation

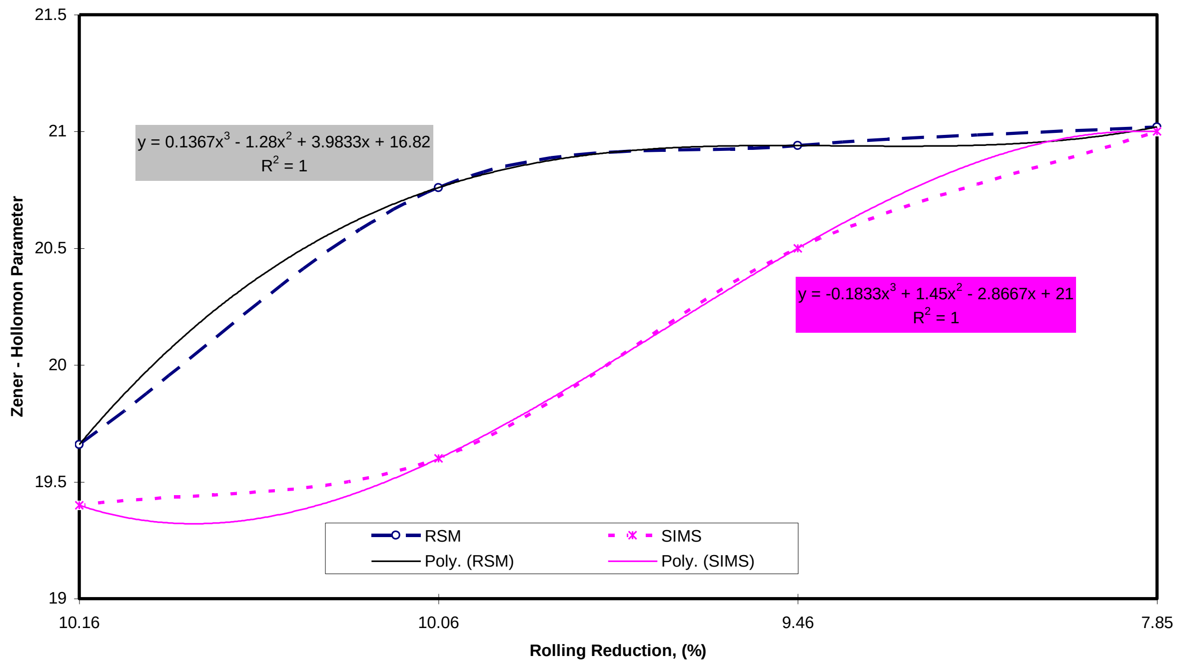

FIG.3: DEPENDENCE OF ZENER - HOLLOMON PARAMETER ON ROLLING REDUCTION BASED ON DIFFERENT ROLLING THEORIES

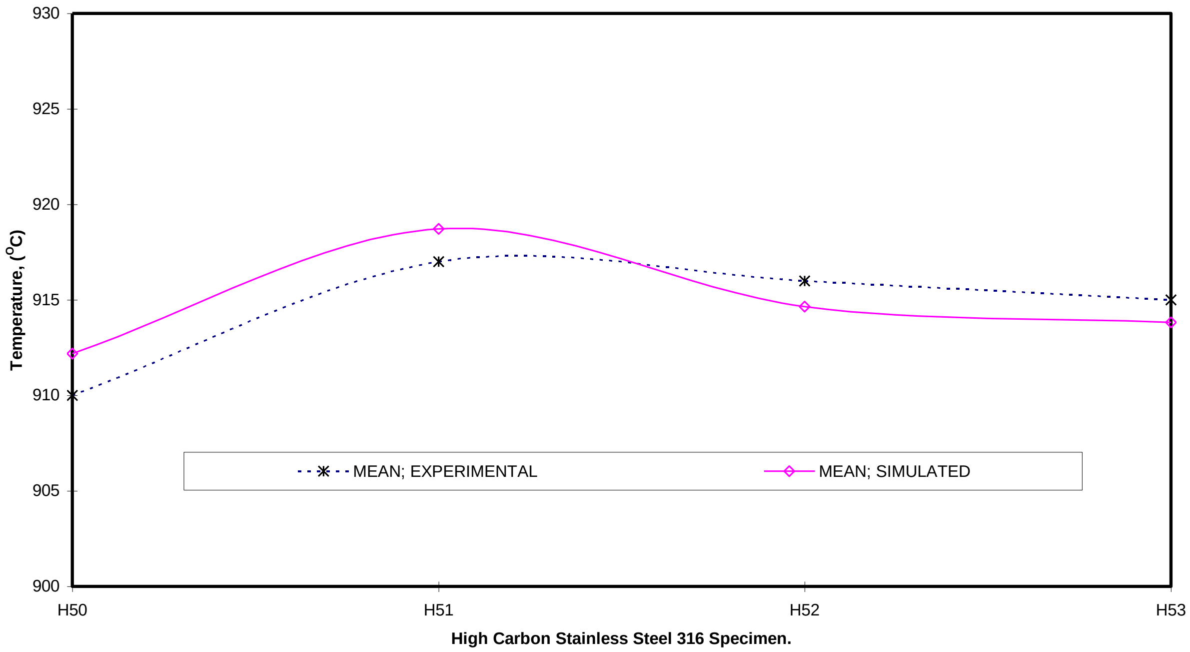

Fig. 4: VALIDATION OF SIMULATED RESULTS USING MEAN ROLLING TEMPERATURE ESTIMATION