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BENCHMARKING AND VALIDATION OF HOT ROLLING SIMULATION MODELS

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ABSTRACT

Mathematical models representing the various stages in the hot rolling process of steel production were produced. Simulated models used were validated using the EXCEL package and then subjected to a sensitivity analysis under identical conditions to predict the optimum operating conditions under which the essential process steps can be carried out.

The results showed that ferrite grain size is more sensitive to the retained strain than to the cooling rate or the austenite grain size. It was also inferred from the work that a drop in the austenite-ferrite (γ - α) transformation temperature leads to an increase in the tensile strength of the steel. This is in agreement with industrial practices.

Keywords: Process modeling, hot strip rolling, mechanical properties, simulation.

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Notation

Symbol	Meaning	Unit
D	Grain size	Microns
D_o, d_o	Initial grain size	Microns
T	Temperature	^oC
t	Time	Second
MFS, σ , σ_n , σ_m	Mean flow stress	MPa
σ_{ss}	Steady state stress	MPa
σ_s	Saturation stress	MPa
σ_p , σ_{SAT}	Peak stress	MPa
ε	Strain	-
ε_p	Peak strain	-
σ_{DYN}	Dynamic recrystallization stress	MPa
ε'	Strain rate	/second
ε_{dyn}	Dynamic recrystallization strain	-
ε_c	Critical strain	-
ε_s	Saturation strain	-
ε_r	Retained strain	-
σ_d	Dislocation strengthening	MPa
σ , YS, L.Y.S., σ_y	Lower yield stress	MPa
σ_y , T_s	Tensile strength	MPa
Z	Zener-Hollomon parameter	-
X, X_{rec}, F.S, X_{st}, X_{RX}	Fraction recrystallized	-
t_{50}, $t_{0.5}$, $t_{50\%}$, $t_{X0.5}$	Time for 50% recrystallization	Second
Q	Activation energy	KJ/mol
R	Universal constant	KJ/mol
SRX	Static recrystallization	-

Q_{RX}, Q_s	Activation energy for static recrystallization	KJ/mol
d_{SRX}, d_{rcx}, D_r, D_{ST}, D_{st}	Static recrystallization grain size	Microns
S_v	Grain surface to grain volume ratio	-
Q_d	Deformation activation energy	KJ/mol
D_g	Grain size after grain growth	Microns
t_g	Time allowed for grain growth	Second
Q_{gg}	Activation energy for grain growth	KJ/mol
t_{ip}	Interpass time	Second
$T_{95\%}$	Time for 95% or full recrystallization	Second
d_γ, D_γ	Austenite grain size	Microns
X_{DR}, X_{dyn}	Dynamically recrystallized fraction	-
D_{dyn}, d_{dyn}, D_{DRX}, D_{RX}	Grain size after dynamic recrystallization	Microns
D_{mdrx}, d_{md}, d_{DMRX}, D_{MD}, D_{mrx}, d_{mrx}	Grain size after metadynamic recrystallization	Microns
D_p, D_{PR}, D_v	Partially recrystallized grain size	Microns
C.R., α, T', C_r	Cooling rate	°C/second
d_α, D_α	Ferrite grain size	Microns
C_{eq}	Carbon equivalent	Weight %
$T_{0.05f}$	Temperature at which transformation begins	°C
T_{mf}	Mean transformation temperature for ferrite	°C
V_f, X_f	Volume fraction of ferrite	-
S_o	Pearlite interlamellar spacing	Microns
H_f	Transformed phase hardness for ferrite	Brinell
H_p	Transformed phase hardness for pearlite	Brinell
V_p	Volume fraction for pearlite	-
H_b	Transformed phase hardness for bainite	Brinell
V_b	Volume fraction for bainite	-
Nb_{eff}	Effective Niobium concentration	Weight %
Q_{md}	Activation energy for metadynamic recrystallization	KJ/mol
T_{50MDRX}	Time for 50% metadynamic recrystallization	Second
$[Nb]_{eq}$	Equivalent Niobium concentration	Weight %
T_{nr}, T_{NRX}	No recrystallization temperature	°C
K_s	Supersaturation ratio	-
$P_{0.05}$, $t_{0.05p}$, t_{ps}, $R_{0.05}$	Precipitation time	Second
HSLA	High strength, low alloy	-
fcc	Face centred cubic	-

INTRODUCTION

Historically, the development and advancement of societies have been intimately tied to members' ability to produce and manipulate materials to fill their needs (William, 1997 and Phaniraj et al, 2000). Early civilizations have been designated by the level of materials development, i.e., Stone Age, Bronze Age (Odewole, 2003). The development of many technologies that make human existence so comfortable has been intimately associated with the accessibility of suitable materials.

Steels are one of the most commonly used construction materials. A new class of steels is the low alloy, high strength variety. The versatility of steel for structural and constructional applications rests on the fact that it can be readily supplied in a wide range of different product forms and with a useful range of materials properties, the use of method which imparts such important characteristics on them during their production should be carefully looked into, and hence, the choice of the hot rolling process for steel production.

Research into controlled hot rolling modeling and simulation has been going on since the 1960's (Tamura et al, 1988, Laasraoui and Jonas, 1991). Many models have been suggested over the years, by researchers, to simulate the full range of the different stages in hot, controlled rolling. A detailed review of these models is available in literatures (Cser et al, 1999, Phaniraj et al, 2000). These models have saved steel industries all over the world millions of dollars; for they have considerably reduced the number of experimental test runs needed for the production of steel with improved properties needed in structural and constructional applications. Different

researchers have used different experimental methods to carry out such simulation; depending on the amount of total deformation, strain rates, temperature, and types of simulation equipment available (Tadeusz, 1992, Medina et al, 1996, Bai et al, 1996 and Djaka et al, 1997 Phaniraj et al, 2000, etc). Laboratory hot rolling, hot compression tests, hot torsion tests and tensile tests have been the most common.

Since the ultimate aim of a modeller is to predict as accurately as possible the mechanical properties of micro-alloy steels for utilization in design and production; reheating of the steel before rolling must be accurately taken care of so that the casting yield of the steel and the products quality could be effectively optimized. Other important factors include flow stress, static recrystallization, peak stress, dynamic recrystallization, metadynamic recrystallization, grain growth, no-recrystallization temperature, precipitation kinetics, partial recrystallization, accumulated strain and ferrite transformations which are thermo-mechanical properties covering the entire span of the hot rolling.

The present work aims at providing ways by which the casting yield of the different steels can be greatly improved, the development of more energy-efficient processing technology for the steels and the determination of models that will optimize products' quality and the process efficiency of the hot rolling.

MATERIALS AND METHODS

Experiments were carried out to determine the behaviour of some steel samples to ascertain the strains, strain rates, temperatures and other parameters affecting the production and casting yield of steel. The steel samples were specially brought from Finland and some of their properties were already known and detailed in Table II. Tests on these were in uniaxial tension, torsion and compression of axially symmetrical or plane samples. Surface treatment and preparation were carried out on the specimens. These operations prepared the specimens used for a later metallographic studies conducted on them for the determination of the crystal grains, their sizes and grain growth which occurred due to the heat treatment the samples were subjected to.

The current concerns of major steel producers which involve the protection of the environment and competition from mini-mills, upgrading the quality of the product by improving the adaptive control systems, introducing tool steel rolls to reduce roll wear, reduction in the cost of production by eliminating non-essential process steps, many of which are energy – intensive and elimination of the reheating process in favour of dynamic recrystallization have become imperative. More importantly, new methods are being for direct casting and rolling of thin strips. Mathematical modelling and simulation of the properties of hot rolled products are being used so that the models constructed could be easily manipulated to yield a motion picture of reality. For this work, these in addition to the use of the EXCEL package generated data which were later combined with the earlier obtained experimental results and adequate "adjustments" were made between these values and those available from industries and mills, with the result that better operating conditions were proposed for the hot rolling process used in production of steel.

There are several possible objectives that may justify the mathematical modelling of the hot rolling process. These include the analysis of metal flow and or the metallurgical events during and after the pass, the off-line scheduling of the draft, the on-line adaptive control of the process or the design of the mill: the rolls, the frame, the drive spindle, the bearings, or the screwdown system.

RESULTS AND DISCUSSIONS

Appendices 1 and 2 give the values of the parameters used in the validation of the simulated models. The results obtained from the validation of the models in the process steps are as presented in Table II. A comparison of these results with those of the Carbon-Manganese (C-Mn) steels is carried out in Table III. The comparison made here are those obtained from the averaging out of the results with similar averaged values for the C-Mn steel for the hot, controlled rolling process. This reveals a possible influence of both the micro-alloys and the substitutional elements on the properties of the different steel produced.

The major microstructural changes that occurred due to the addition of both micro-alloys and substitutional elements are grain refinement due to recrystallization and strain – induced precipitation of the carbo-nitrides. The strengthening of the steel obtained are through precipitation hardening and the refinement of the ferrite grains through reduction of the austenite – ferrite (γ-α) transformation temperature.

The percentage compositions of additives used for the validation of the simulated models are presented in Table I. From Table II, it is evident that the presence of the additives, i.e., the micro-alloys and the substitutional elements strengthens the steel, however, there is an increase in the solubility of the elements as indicated by the high temperature (1213°C) obtained when compared with that of the C-Mn steel (Table III). This rise in temperature is an indication of the increased energy used in the reheating of the slab. These strengthening factors are present from the reheat stage and up to the transformation which occurred in the ferrite stage of the hot rolling process and may therefore, be responsible for the increase in softening times for both static and metadynamic recrystallization (2 to

12.80s and 0.52 to 3.79s respectively) in comparison with the C-Mn steel.

The reduction in static and metadynamic grain sizes (from 35 to 30.5 microns, and from 32 to 20.9 microns respectively) contributed to producing steel with small, uniform ferrite grains which improves the mechanical properties of the products. Another contributing factor is reduced grain growth after metadynamic recrystallization (from 54.60 to 43.10 microns). These occur as a result of the greatly refined microstructure formed.

The reductions and refinement obtained through the changes that occurred above led to a higher ultimate tensile strength (a change from 480.5 to 796 MPa).

Table 1: Percentage Composition of Additives Used

*Const.	Percentage Composition															
	C	Si	Mn	Nb	S	P	V	Cr	Ni	Mo	Ti	Cu	Al	B	N	H
Mo-Ti	0.06	0.47	1.49		.005		0.08						042		0.013	
Si-Mn	0.03	0.5	1.21	0.01	.001	.036	.031	18.1	10	0.15	.006	0.19	.055		0.03	
V-T	0.03 -	0-0.21	0.24 -		0.02	0.008-							0.02 -		0.003 -	
IF-Mo	0.45		1.08			.017							042		0.005	
A36	.155	.259	1.51		.031		0.12								0.015	
1538V	.112	1.26	1.53		.008	.013		.021	022				029		.0017	
Mo-VNb	0.21	0.06	0.79		.013		0.01	0.84	0.12	0.31			.046		0.02	
IF	1.1	0.23	0.63		007	0.01	0.17	0.04	038			.036			0.007	
Cr-Mo	0.18	0.33	1.33	.003			003	.012			.003					
Ti-V	.310	.084	0.67					1.04					.027	002	.0077	
Cr-B	0.18		1.30	.035												
Nb-B	.090-	0.30-	1.30-													
Nb-Ti-V	0.14	0.47	1.60													
Nb-Ti	.150	0.35	1.39	024	.003	.018					.018		.024	.027		3[ppm]
Nb-Ti	0.09	0.23	1.51	033							.015					
Nb-Ti	0.08	0.39	1.65	0.04			.003			.004	.012		.026		.0039	
Cu-Nb-B	026	0.18	1.38	.058	.006	.007					017	2.03	.019	.003	0.006	
Mo1	0.44	0.24	0.79							0.26						
V3	0.11	0.24	1.00				.093								0144	
Mo-Ti	063	220	1.20		008	011				0.18	0.02		029		27ppm	
Mo	.063	0.22	1.20	-	008	011				0.18	.029		.029		27 ppm	
IF	008	011	0.29	.055	012	008					0.13		049		.0066	
310SS	0.25	1.50	0.20					25.0	22.0							
Ti1	0.15	0.24	1.12								.021				0.015	
V-T	0.12	362	1.42		.014	.017	.042								.0095	
Mo2	0.44	0.23	0.79							0.38					-	
V1	0.11	0.24	1.10				043								.0105	
Mo-NbB	026	120	1.70	059						0.30	.015		.037	.004	0.003	
Mo4	.063	0.22	1.20	-	.008	011				0.18	.029		.029		27 ppm	
Cr3	0.55	0.31	0.78		.002	.007		0.76	0.07	0.02		0.1	.004	.005		
Cr-Mo-V	0.47		0.66	016			0.12	0.98	0.46	0.97					.0042	
C	.038	009	0.30	-	008	.010	-				-	015	0.04		.0052	
Mo-B	0.08		1.5	045			0.08				.015					

Source: Phanniraj et al, 2000.

*Const. Steel designation based on major constituent

Table II: Validated Models for Other Types of Steels

Table II A: Solubility Models

MD. NO	*CONST.	MODEL	Value(^{o}C)
1	V	$T=8700[1/\{3.63-Log[V][N]\}]$	1284.58
2	V	$T=8330[1/\{3.40-Log[V][N]\}]$	1302.79
3	V	$T=9500[1/\{6.72-Log[V][C]\}]$	1213.61
4	V	$T=7840[1/\{3.02-Log[\%V][\%N]\}]$	1329.68
		Grain Growth in Reheating	
NO.	CONST.	MODEL	Value
		Isothermal Grain Growth Model	(Microns)
5	Si-Mn	$d^{n}=d_o^{n}+k_1t^{*}\exp(k_2/T)$	52.85
		Grain Size in Continous Reheating Model	
6	Si-Mn	$d_q=(0.60661/l_m)^4(A_m/0.4861)^{5/2}$	46.50

Table II B: Flow Stress Models

MD. NO.	*CONST.	MODEL	Value (MPa)
7	IF	$\sigma=K(\varepsilon+\varepsilon_o)^{n}(\varepsilon'/\varepsilon'_o)^{m}(1+\beta(T-T_o))$	71.43
8	Mo	$\sigma_1=\sigma_s^{*}(1-\exp(-\varepsilon-\varepsilon_r^{*})^{0.5})$	380.21
9	"	$\sigma=\sigma_1-(\sigma_s^{*}-\sigma_{ss})(1-\exp(-\beta_{dyn}(\varepsilon-\varepsilon_p)^{n}))$	417.08
10	Cr-Mo	$MFS^{*}_{Cr\text{-}Mo}=(MFS_{misaka}(0.835+0.51Nb+0.098Mn+0.128Cr^{0.80}+0.144Mo^{0.3}+0.175V+0.01Ni))^{*}(1-X_{dyn})+K\sigma_{ss}X_{dyn}$	402.11

Table II C: Static Recrystallization

Kinetics of Static Recrystallization Models

MD. NO.	*CONST.	MODEL	Value(s)
11	Mo-Ti-Nb	$t_{0.5}=A\varepsilon'^{q}\varepsilon^{p}D_s\exp(Q/RT)$	62.08
12	V	$T_{0.5}=A'\exp(Q^{*}/RT)$	2.55
13	"	$t_{0.5}=A_sd_o\varepsilon^{\beta}\varepsilon'^{1.3}\exp(Q_s/RT)$	0.37
14	Nb-B	$t_{0.5}=2.86*10^{-19}\varepsilon^{-3.80}\varepsilon'^{-0.42}\exp(436000/RT)$	101.78
15	"	$t_{0.5}=1.06*10^{-24}\varepsilon^{-3.55}\varepsilon'^{-0.33}\exp(559000/RT)$	28.20
16	Nb-Ti	$t_{0.5}=3.677*10^{-20}D^2(\varepsilon-0.08)^2\varepsilon'^{-0.176}\exp(359000/RT)$	0.01
17	"	$t_{0.5}=1.6*10^{-14}\varepsilon^{-1.7}\varepsilon'^{-0.42}d_o^{0.7}\exp(360000/RT)$	2277.70
18	Nb-Ti-Mo	$t_{0.5}=Ad_o^{2}\varepsilon^{-\gamma}\exp(Q/RT)$	81.71
19	V	$T_{0.5}=1.033*10^{-10}\varepsilon'^{-0.44}\varepsilon^{-2.6}Dexp(158000/RT)$	1.04
20	"	$T_{0.5}=3.7100*10^{-12}\varepsilon'^{-0.44}\varepsilon^{-2.6}Dexp(205000/RT)$	3.16
21	CrMo-VNb	$T_{0.5}=1.57*10^{-14}\varepsilon^{-2.9}d^2\exp(271000/RT)$	55.44
22	Nb-Ti	$t_{0.5}=3.677*10^{-20}D^2(\varepsilon-0.08)^2\varepsilon'^{-0.176}\exp(359000/RT)$	70.01
23	Mo-Ti	$T_{0.5x}=1.5*10^{-12}\varepsilon^{-0.28}\dot{\varepsilon}^{-2.18}D^{-0.87}\exp[232000/RT]$	28.21
24	Ti-V	$t_{0.5x}=5*10^{-18}(\varepsilon-0.085)^{-3.5}D^2\exp[280000/RT]$	7.53
25	Eutectoid	$t_{0.5x}=2.4*10^{-8}\varepsilon^{p}\dot{\varepsilon}^{-0.29}D^{-0.2}\exp[160420/RT]$	1.37
26	V-T	$t_{0.5x}=9.3*10^{-13}\varepsilon^{-4}D^2\exp[230000/RT]$	4.03
27	Austenitic	$T_{50}=2.29*10^{-15}\varepsilon^{-2}Z^{-0.32}\exp(400000/RT)$	0.17

Table II C Contd.

28	Cr-Mo	$T_{0.5}=1.57*10^{-14}d_o^{2}\varepsilon^{-2.9}\exp(271000/RT)$	55.44
29	A36	$t_{0.5}=8.31*10^{-15}d^{1.5}\varepsilon^{-1.5}\dot{\varepsilon}^{-0.33}\exp(263000/RT)$	2.05
30	4120 1538V	$t_{0.5}=V2^{*}\ \dot{\varepsilon}^{-g3}d_o^{g4}\varepsilon^{-g5}\exp(L1/RT)$	0.16
31	Cr	$t_{0.5}=2.75*10^{-11}\ \dot{\varepsilon}^{-0.125}\varepsilon^{-2.45}d^{1.06}\exp(184000/RT)$	3.20
		Static Recrystallization Grain Size Models	
NO.	CONST.	MODEL	Value (Microns)
32	Ti-V	$D_{rex}^{y}=B+CD_o^{x}\varepsilon^{-y}[\exp(350000/RT)]^{-z}$	11.04
33	V	$d_{rex}=\Lambda d_o^{1/3}\varepsilon^{-p}\exp(-Q_{gx}/RT)$	41.65
34	V-Ti-Nb	$D_{rex}^{y}=B+CD_o^{x}\varepsilon^{-y}[\exp(350000/RT)]^{-z}$	11.20
35	Nb-V	$D_{rex}^{y}=-1.25+24.4(V+Nb)^{-0.2}N^{-0.04}D_o^{0.25}\varepsilon^{-0.55}[\exp(35000/RT)]^{-0.7}$	11.80
36	Ti-V	$D_r=4.3+195.7D^{0.15}\varepsilon^{-0.57}\exp[-350000/RT]$	43.01
37	Eutectoid	$D_r=9.91D^{0.54}\varepsilon^{-0.65}\ \dot{\varepsilon}^{-0.1}\exp[-17540/RT]$	44.46
38	V-T	$D_r=4.54D^{0.67}\varepsilon^{-0.53}\ \dot{\varepsilon}^{-0.1}\exp[-15000/RT]$	35.49
39	Austenitic	$D_r=2.24\varepsilon^{-0.5}DZ^{-0.06}$	45.70
40	"	$D_r=83.9\varepsilon^{-0.537}D^{0.355}Z^{-0.0655}$	124.66
41	Cr-Mo	$d_{SRX}=1.1d_o^{0.67}\varepsilon^{-0.67}$	44.46
42	A36	$d_{rex}=88.96d_o^{0.36}\varepsilon^{-0.368}\exp(-28060/RT)$	46.38
43	4120 1538V	$d_{srxn}=V3*d_o^{g6}\varepsilon^{-g7}\exp(-L2/RT)$	37.89

Table II C: Static Recrystallization

		Grain Growth After Static Recrystallisation	
NO.	CONST.	MODEL	Value (Microns)
		Growth During 1st Second Model	
44	Cr-Mo	$d^2=d^2_{SRX}+4.0*10^{7}(t_{ip}-4.32t_{0.5})\exp(-113000/RT)$	30.12
		Growth After 1st Second Model	
45	"	$d^7=d^7_{SRX}+1.5*10^{27}(t_{ip}-4.32t_{0.5})\exp(-400000/RT)$	50.30

Table II D: Dynamic Recrystallization

Critical and Peak Strains Models

MD. NO.	*CONST.	MODEL	Value
46	CrMoV	$\varepsilon_p=0.0040d^{0.50}[\varepsilon'\exp(241000/RT)]^{0.17}$	1.36
47	Nb	$\varepsilon_c=0.84\varepsilon_p$	1.14
48	V	$\varepsilon_p=4.3*10^{-3}D^{0.20}Z^{0.174}$	1.31
49	"	$\varepsilon_p=5.9*10^{-3}D^{0.20}Z^{0.174}$	1.79
50	Mo	$\varepsilon_p=5.24*10^{-4}D_o^{0.5}Z^{0.18}$	0.61
51	Mo-Ti	$\varepsilon_p=7.07*10^{-4}dZ^{0.15}$	2.49
52	4120 1538V	$\varepsilon_p=A1*d_o^{b1}\dot{\varepsilon}^{b2}\exp(P1/RT)$	0.50
53	"	$\varepsilon_c=0.83\varepsilon_p$	0.42
54	A36	$\varepsilon_p=0.01318d_o^{0.174}\dot{\varepsilon}^{0.165}\exp(2926/T)$	0.26

Table II D Contd.

55	"	$\varepsilon_c=(5/6)\varepsilon_p$	0.22
56	4120 1538V	$\varepsilon_c=C(V1*d_o^{g1}*Z^{g2})$	0.33
57	Cr	$\varepsilon_p=4.2*10^{-4}d^{1/2}Z^{0.15}$	0.21
Kinetics of Dynamic Recrystallization Models- (Volume Fraction X)			
NO.	CONST.	MODEL	Value
58	Cr-B	$X_{DR}(\varepsilon)=1-\exp\{-2.996[(\varepsilon-\varepsilon_c)/(\varepsilon_s-\varepsilon_c)]^n\}$	0.35
59	"	$X_{DR}(\varepsilon)=1-\exp\{-2.996(\varepsilon/\varepsilon_s)^n\}$	0.27
60	"	$X_{DS}(\varepsilon)=1-\exp\{-3[\varepsilon/\varepsilon_s(\varepsilon',T)]^{n(\varepsilon)}\}$	0.27
61	Mo	$X_{dyn}=(\sigma_s^*-\sigma)/(\sigma_s^*-\sigma_{ss})=1-\exp(-\beta_{dyn}(\varepsilon-\alpha\varepsilon_p)^n$	0.13

Table II E: Metadynamic Recrystallization

Kinetics of Metadynamic Recrystallization Models

MD. NO.	*CONST.	MODEL	Value(s)
62	Mo-Ti	$t_{0.5}=6.66*10^{-6}\varepsilon'^{-0.51}\exp(136000/RT)$	2.54
63	"	$t_{0.5}=6.66*10^{-6}\varepsilon'^{-0.71}\exp(110000/RT)$	2.20
64	Mo	$t_{50\%}=6.66*10^{-6}\varepsilon'^{-0.61}\exp(123000/RT)$	7.50
65	V	$t_{0.5}=A_{md}\varepsilon'^{-2/3}\exp(Q_{md}/RT)$	2.50
66	V-Ti	$t_{50\%}=1.8*10^{-6}d_o^{0.24}\varepsilon'^{-0.75}\exp(13974/T)$	2.70
67	V	$t_{0.5}=(1.5([Si]+[V]+2.8)*10^{-8}Z^{-0.6}\exp(380/RT)$	3.20
68	"	$t_{0.5}=(1.5([Si]+[V]+2.8)*10^{-8}\varepsilon^{-0.6}\exp(170/RT)$	4.28
69	A36	$t_{0.5}=2.13*10^{-6}\dot{\varepsilon}^{-0.68}\exp(132800/RT)$	6.00
70	4120 1538V	$t_{0.5}=V4*Z^{-g8}\exp(L3/RT)$	2.53
71	"	$t_{0.5}=V4*\dot{\varepsilon}^{-n1}d_o^{n2}\varepsilon^{-n3}\exp(L3/RT)$	2.91
72	Cr-Mo	$t_{0.5}=1.84*[\dot{\varepsilon}\exp(330000/RT)]^{-0.86}\exp(271000/RT)$	5.50
73	Cr	$t_{0.5}=3.5*10^{-2}\dot{\varepsilon}^{-0.785}\exp(24800/RT)$	3.60
Metadynamic Recrystallization Grain Size Models			
NO.	CONST.	MODEL	Value (Microns)
74	Mo	$D_{mdrx}=1.66*10^3Z^{-0.16}$	17.78
75	Mo-Ti	$D_{MDRX}=1.19*10^3Z^{-0.16}$	12.75
76	Cr-Mo	$d_{MDRX}=1370*\varepsilon^{-0.13}\exp(-45000/RT)$	20.41
77	4120 1538V	$d_{Drxn}=V5*Z^{-g9}$	31.07
Grain Growth After Metadynamic Recrystallization			
NO.	CONST.	MODEL	Value (Microns)
Growth During 1st Second Model			
78	Cr-Mo	$d^2=d^2_{MDRX}+1.2*10^7(t_{ip}-2.65t_{0.5})\exp(-113000/RT)$	58.79
Growth After 1st Second Models			
79	Cr-Mo	$d^7=d^7_{MDRX}+8.2*10^{25}(t_{ip}-2.65t_{0.5})\exp(-400000/RT)$	32.50
80	"	$d^{4.5}=d_o^{4.5}+4.1*10^{23}*t_{ip}*\exp(-435000/RT)$	46.09

Table II F: Non-Recrystallization Temperature Models

MD. NO.	*CONST.	MODEL	Value(°C)
81	Mo-B	$T_{nr}=A\varepsilon^{-0.12}\varepsilon'^{-0.01}t^{-0.1}$	815.20
82	Nb-B	$T_{nr}=(A'Log[C][Nb]+B')\varepsilon^{-0.12}\varepsilon'^{-0.01}t^{0.04}$	945.63

Table II G: Kinetics of Precipitation Models

MD. NO.	*CONST.	MODEL	Value(s)
83	Nb-Ti	$R_{0.05}=0.33*10^{-19}d_o^{2}\varepsilon^{-4}\exp(360000/RT)$	2.89
84	"	$R_{0.05}=2.89*10^{-38}d_o^{2}\varepsilon^{-4}\exp(780000/RT)$	8.81

Table II H: Ferrite Grain Size Models

MD. NO.	*CONST.	MODEL	Value (Microns)
85	V-Ti	$D_\alpha=3.75+0.18D+1.4Cr^{-0.5}$	13.27
86	"	$D_\alpha=(1-0.45\varepsilon_r^{1/2})*\{3+1.4Cr^{-1/2}+17[1-\exp(-1.5*10^{2}D)]\}$	19.08
87	V-T	$D_\alpha=(D/(1+(0.036+0.0233Cr^{0.5})D))$	12.09
88	Nb-V-Ti	$D_\gamma/D_\alpha=1+(0.0026+0.053\%C+0.006\%Mn+0.009\%Nb+4.23\%V*N-0.081\%Ti)*(1.5+\alpha^{1/2})*D_\gamma$	10.12

Table II I: Lower Yield Stress Models

MD. NO.	*CONST.	MODEL	Value (MPa)
89	V	$LYS=62.6+26.1[Mn]+60.2[Si]+759[P]+212.9[Cu]+3286.0[N]+\sigma_{ppn}+19.7d\alpha^{-0.5}$	562.05
		Models Relate Lower Yield Stress to Mean Free Path in Ferrite	
90	Eutectoid	$\sigma_y=308+0.07(1/M)$	308.23
91	"	$\sigma_y=259+0.087(1/M)$	259.44
92	V	$LYS=70+84Si+32Mn+680P+33Ni+38Cu-30Cr+1.81d^{-1/2}$	163.45

Table II J: Models Describing Contribution of Precipitation to Strengthening(L.Y.S)

MD. NO.	*CONST.	MODEL	Value (MPa)
93	V	$\sigma_p=57LogCr+700[V]+7800[N]+19$	16.20
94	"	$\sigma_p=19.9[C]+552.8[C]^{2}+590[V]+8650[N]+19.9\ln(Cr)$	15.82
95	Nb-Ti	$\sigma_p=2500([Nb]*-0.5[Ti])$	50.00

Table II K: Tensile Strength Models

MD. NO.	*CONST.	MODEL	Value (MPa)
96	V	$TS=164.9+634.7[C]+53.6[Mn]+99.7[Si]+651.9[P]+472.6[Ni]+3339.4[N]+\sigma_{ppn}+11d\alpha^{-0.5}$	796.49
97	Eutectoid	$\sigma_u=706+0.072(1/M)+122[Si]$	763.58
98	"	$\sigma_u=773+0.058(1/M)+122[Si]$	830.63

Models Sources: Cser et al, 1999. *Phaniraj et al, 2000.*

Table III: Comparisons Between C-Mn and Other Types of Steels

Steels / Models	*C-Mn	Other Types
Solubility (°C)	1203	1213
Grain Growth in Reheating (Microns)	40.7	50
Flow Stress (MPa)	208	392
Static Recrystallization, t_{50} (Second)	2	12.8
Static Recrystallization Grain Size (Microns)	35	30.5
Static Recrystallization Grain Growth (Microns)	45.5	43.8
Metadynamic Recrystallization, t_{50} (Second)	0.52	3.79
Metadynamic Recrystallization Grain Size (Microns)	32	20.9
Metadynamic Recrystallization Grain Growth (Microns)	54.6	43.1
Ferrite Grain Size (Microns)	10.8	13.5
Lower Yield Stress, L.Y.S (MPa)	331.2	323
Ultimate Tensile Strength, U.T.S (MPa)	480.5	796

*: ***Phaniraj et al, 2000.***

CONCLUSION

The following conclusions can be drawn:

1. Ferrite grain size is more sensitive to the retained strain than to the cooling rate or the austenite grain size. However, there is a limit to the size of the ferrite grain that can be obtained by increasing the retained strain or the cooling rate.
2. A drop in the austenite-ferrite (γ-α) transformation temperature leads to an increase in the tensile strength of the steel.
3. The use of the computer in the validation of the simulated models reduces the number of experimental test runs needed for the formulation and determination of process parameters required in steel production.

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Appendix 1

Values Used in the Validation of the Simulated Models

Unless otherwise stated, the general values of the parameters utilized in validating the simulated models are as follows:

1. **Reheating Before Rolling**

Solubility Models

C = 0.1 wt %, N = 0.02 wt %, V = 0.09 wt %, Al = 0.025 wt %, D_o = 40 microns, T = 1473K.

Grain Growth in Reheating

D_o = 25 microns, T = 1473 K, t 30 mins, R = 8.312 KJ mol.

2. **Flow Stress**

Strain Rate = 1 s, R = 8.312 KJ mol, T = 1273 K, [C] = 0.03 wt %, [Mn] = 0.27 wt %, X_{dyn} = 0.8, Strain = 0.2, Q_{RX} = 300000 J mol, Q_d 330000 J mol, Peak Strain, ε_p = 0.35.

3. **Kinetics of Static Recrystallization**

R = 8.312 KJ mol, T = 1273 K, Do = 50 microns, Q_d = 330000 J mol, Q_{rex} = 480000 J mol, X^4 = 0.5, Strain rate = 1 s, Strain = 0.2, [Mn] = 1.4 wt %.

Static Recrystallization Grain Size

D_o = 50 microns, Strain = 0.2, R = 8.312 KJ/mol, T = 1273 K, Q_d = 330000 J/mol.

Grain Growth after Static Recrystallization

$t_{0.5}$ = 10s, $t_g = t_{ip}$ = 50s, d_{rex} = 30 microns, $t_{0.5e_p}$ = 20s, R = 8.312 KJ/mol, T = 1273 K.

4. **Dynamic Recrystallization**

Critical and Peak Strain

Q_{drx} = 312000 KJ mol, Q_d = 330000 J/mol, D_o = 50 microns, T = 1273 K.

5. **Kinetics of Metadynamic Recrystallization**

D_o = 40 microns, Strain Rate = 1/s, K = 1.7, R = 8.312 KJ/mol, T = 1273 K.

Metadynamic Recrystallization Grain Size

Q_d 330000KJ mol, Strain Rate = 1/s, T = 1273 K, R = 8.312 KJ/mol.

Grain Growth after Metadynamic Recrystallization

t_{ip} = 20s, T = 1273 K, D_{mdrx} = 22 microns, R = 8.312KJ/mol, $t_{0.5}$ = 1s.

6. **No Recrystallisation Temperature, Tnr**

t = 15s, T = 1123 K.

7. **Ferrite Grain Size**

C_{eq} = 0.14 wt %, D = 22 microns, α = 3°C/s, T = 1273K, Retained Strain = 0.1, X_f = 0.9, D=40 microns

8. **Lower Yield Stress**

Si = 0.33 wt %, N = 0.02 wt %, Mn = 1.3 wt %, X_f = 0.9, D = 10 microns, C = 0.18 wt %, α = 3°C/s, D = 40microns, T =1273 K, Cu = 0.009 wt %, [P]= 0.009 wt %,

9. **Contribution of Precipitation to Lower Yield Stress (L.Y.S)**

[V] = 0.09, [N] = 0.02, [C] = 0.1, C.R. = 3°C/s, [Ti] = 0.003.

10. **Tensile Strength.**

[C] = 0.1 wt %, [Mn] = 1.33 wt %, [Si] = 0.25 wt %, [P] = 0.009 wt %, [Ni] = 0.009 wt %, D = 10 microns, X_f = 0.9.

Appendix 2

The parameters listed below are specific and have been used to validate the simulated models listed above either wholly by themselves or in conjunction with the general parameters listed in appendix 1.

SPECIFIC PARAMETERS, VALUES AND REMARKS
When the soaking temperature is lower than 1150°C $\log n = 0.531 + 307.404/T$, $K_1 = 8.74*10^4$, $K_2 = 4.264*10^3$ When the soaking temperature is in the range 1150 – 1250°C $\log n = 5.214 + 8406/T$, $K1 = 1.29*10^{-54}$, $K2 = 1.94*10^5$. t = soaking time.
$l_m = 0.60661 d_g \exp(5(\ln s)^2/2)$, $A_m = 0.4861 d^2 \exp(4(\ln s)^2)$ $s = \exp(\ln(1.3211^2_m A_m))^{1/2}$), $d_m = d_g \exp((\ln s)^5/2)$, d_g – Median grain diameter d_m Mean grain diameter, l_m = 10 microns, A_m = 200 μm^2

Appendix 2 Contd.

K=566MPa, ε_0=-0.014, n=0.219, β=-0.0012, m =0.018, ε'_0=0.02/s, T_o =298K
Q_d=296kJ/mol, $\varepsilon_p = 2.84*10^{-4}D_0^{0.5}Z^{0.17}$, $\beta_{dyn} = 48\varepsilon'^{-0.22}\exp(-41060/RT)$ $n = 0.23\varepsilon'^{-0.11}\exp(18000/RT)$, $\sigma_{ss} = 7.4Z^{0.096}$
Valid for 0.52 – 0.66%Mn, 0-0.8% Nb, 0.83 – 1.38% Cr, 0-0.46%Ni, 0.15-0.97% Mo, and 0-0.27% V $\sigma_{ss} = 1.18[\varepsilon'\exp(330000/RT)]^{0.15}$
$Q = 124714 + 28285.68[Mn]+64716.68[Si]+72775.40[Mo]+76830.32[Ti]^{0.213}+$ $121100.37[Nb]^{0.1}$, $A = 3.869.10^{-4}\exp(-7.921.10^{-5}Q)$, s = 1, q = -0.53, p =3.7$d^{-0.13}$
$A = 25.3318\exp(-1.0147.10^{-4}Q^*)$, $Q^* = Q\exp[H/R(1/T-1/SRCT)]$ $H = 400000\ Jmol^{-1}$, $SRCT(K)_V = T_s - 1.05.10^3 D^{-0.35}\varepsilon^{0.50}$
$A_s = 5.15.10^{-15}$ s, β = 2.0, Q_s = 262kJ/mol
$A = 1.8*10^{-28}$, y = -4.6, Strain = 0.59
T>915 ^{0}C, $Z = \varepsilon'\exp(248000/RT$ T>915^{0}C
Steel 0.06%C, 1.2%Mn, 0.22%Si, 0.18%Mo, 0.02%Ti, 0.029%Al, 0.0027%N
Steel 0.13% C, 1.4_ Mn,0.01% Ti, 0.04% V, 0.01%N
Steel 0.72%C, 1.2% Mn, 0.28% Si, 0.002% Al, 0.21% Cr.
Steel 0.2% C, 1.36% Mn, 0.26% Si, 0.09% V, 0.001% Al, 0.006%N
B = 1.1, C = 170, x =0.15, y=0.57, z=0.11 for 0.01 Ti –(0.08-0.13V)-0.023N
$A=8.9.10^1\mu m^{2.3}$, p = 0.368, Q_{gx} = 28.1 kJ mol
B = 1.08, C=176.2, x =0.02, y = 0.66, z = 0.09 for 0.01 Ti-0.04V-0.025Nb-0.008N
0.04-0.13%V, 0-0.025%Nb, 0.008-0.023%N
Steel 0.13% C, 1.4%Mn, 0.01%Ti, 0.04% V, 01%N
Steel 0.72% C, 1.2% Mn, 0.28% Si, 0.002% Al, 0.21% Cr
Steel 0.2% C, 1.36% Mn, 0.26% Si, 0.09% V, 0.001%Al, 0.006%N
If $d_{rex} > d_o$,then $d_{rex} = d_o$
T>915^{0C}
T>915^{0}C
$n = 0.27\varepsilon'^{0.08}\exp(15.8kJ/mol/RT)$, $\beta_{dyn}=3512-\varepsilon'^{0.3}\exp(-84.7kJ/mol/RT)$
950≤T≤1000^{0}C
$A_{md} = 1.54.10^{-6}$ s, Q_{md} = 127 kJ/mol
A = 88.1^{0}C per wt%, B = 1156^{0}C, t≤12.5s, Nb_{eq}=Nb+0.31Ti+0.15Al
A' =63.5^{0}C per wt%, 12.5 s≤ t ≤30s, B' = 885 ^{0}C
T > 1000^{0}C 1000>T>890^{0}C
Steel 0.2% C, 1.36% Mn, 0.26% Si, 0.09% V, 0.001% Al, 0.006%N
D_γ/D_α - Grain refinement ratio
σ_{ppt}=57logT' + 700[V]+7800[N]+19
M – Mean free path for slip . M = $2S_o$(1-0.15[C]) $S_o \geq 0.15\mu m$ $S_o < 0.15\mu m$
σ_p- Precipitation stress
σ_{ppn} = 57log T' + 700 [V]+7800[N]+19
Steel 0.72% C, 1.2% Mn, 0.28% Si, 0.002% Al, 0.21%Cr in wt. % $S_o \geq 0.15\mu m$ $S_o < 0.15\mu m$, Where M = $2S_o$(1-0.15[C]) S_o ={129.3-54.4[Mn]-4.4[Cr]-17.5[Si]-(0.18-0.07[Mn]-0.012[Cr]-0.027[Si])T_p}$^{-1}$