Review of Research Data Published on 18 Ni-Co-Mo-Ti Maraging Steel, by Viswanathan et al 1993, Lee et al 2007 and Mathematical Modeling Attempt for Ageing time Prediction for 18 Ni-Co-Mo-Ti Maraging Steel and Unveil Parameters which Effect Mathematical Modeling of Heat Treatment

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Abstract
A Mathematical approach towards the prediction of consecutive aging time in 18 Ni-Co-Mo-Ti maraging steels to get desired strength value, for meeting engineering requirement. Taking inspiration from JM Pardal et.al, 2005 and Nong Wang et.al 2005. Data values from U.K Viswanathan 1993 and Lee.2007 have been used for deriving equations. Devised an equation for finding ageing time ,found true for both maraging steel C250 and C350. Modeling is based on the basic understanding that strengthening due to ageing process is the product of ageing time and ageing temperature .

Keywords - *Heat treatment, Heat treatment modeling, Tensile testing, Prediction of aging time, 18 Ni Maraging steel. Desired 02% yield strength.*

I. INTRODUCTION

The development of the nickel maraging steels began in the Inco laboratories in the late 1950s, and was based on the concept of using substitutional elements to produce age-hardening in a low carbon iron-Nickel martensitic matrix [5]. Ironically maraging steel got in focus from the world war era [3].

Age hardening of steels, was sure to happen to property enhancement, One of such notable study was done by H.J Rack in the year 1971, he reported that the optimum aged condition was associated with cross-slip deformation and the fracture behavior of the average condition is a dynamic balance between a brittle matrix and the ductility (crack blunting) reverted austenite [2]. Other important publication regarding Maraging steel aging is by U.K Viswanathan et.al in1993.

Mathematical modeling of the age hardening process became unavoidable since good finding in this regard would save considerable research time. In the year 2005(Pardal,2005) modeled the age hardening of the margin 300 steel between 440°C and 560 °C with the help of Hollomon equation with good correlation coefficients (R).Nong WAN, established a mathematical model that can be used in the prediction of tempering hardness for quenched steel.He used a mathematical resolution equation describing the variation of the tempering hardness with the tempering temperature and the tempering time was deduced by differentiating and integrating Hollomon tempering equation $P = T(C + \lg\tau)$ on the assumption that tempering hardness H belongs to state function[1]. Prior to wang in the year 2004,Gau developed artificial neural network (ANN) model for the analysis and simulation of the correlation between the properties of maraging steels and composition, processing and working conditions. The input parameters of the model consist of alloy composition, processing parameters The outputs of the ANN model include property parameters namely: ultimate tensile strength, yield strength, elongation, reduction in area, hardness, notched tensile strength, Charpy impact energy, fracture toughness, and martensitic transformation start temperature[13]. Although these researchers have given good results they are more into graph fitting ,taking log and complex equations forming .Here am going to introduce a simple arithmetic prediction of aging time to get a desired strength value. With the help of, published data available.

II. A FEW EXAMPLES OF RECENT MATHEMATICAL APPROACHES TOWARDS HEAT TREATMENT MODELING

a)The equation used for stimulating grain growth [9].

$D_0 = (D_3 + A.T.exp\ (-Q_0/E))^f$

$D_0 = D_{gg}\ ,\ D_3 = D_0^{\ e}\ ,t_1 = t_{eq}\ ,Q_0 = Q_{gg},\ e = n_{gg}\ ,\ f = 1/n_{gg}$

$RT_i = E, t_{eq} = T$

b)The equation for calculating recrystallised fraction [9].

$X_{RX} = 1-exp\ .ln0.5.Y^m),$

$here\ (e-e_{cr}\ )/(e_{0.5} - e_{cr}) = Y$

c)The average grain size calculated based on the accumulated plastic work of deformation [12][9].

$DRX = D1+D2.exp(-C.Intgl\ \sigma.\xi.dt)$

III. REPORTED DATA: MARAGING STEEL COMPOSITION[7]

TABLE 1 NOMINAL WT% OF ELEMENTS IN, C350,C250AND C300 MARAGING STEEL.

SL No	Elements	C350	C250	C300
01	Ni	18.00%	18.00%	18.00%
02	Mo	4.20%	5.00 %	5.00%
03	Co	12.50%	8.50%	9.00%
04	Ti	1.60%	0.40%	0.70%
05	Al	0.10%	0.10%	0.10%

NEXT STEP IS COMPARISON OF ELEMENT WT% IN C 250 AND C 350 WITH NOMINAL VALUES .

TABLE 2 (A) COMPARISON OF ELEMENT PERCENTAGE IN C350 .

SL.No	Elements	Nominal Value	Viswanathan,1993
01	Ni	18%	18.39%
02	Mo	4.20%	3.99%
03	Co	12.50%	12.32%
04	Ti	1.60%	1.63%
05	Al	0.10%	0.12%

TABLE 3 (B) COMPARISON OF ELEMENT PERCENTAGE IN C 250.

SL.No	Elements	Nominal Value	Lee,2007
01	Ni	18%	17.60%
02	Mo	5.00%	4.90%
03	Co	8.50%	8.60%
04	Ti	0.40%	0.50%
05	Al	0.10%	0.15%

NEXT WE SEE ,REPORTED DATA:MARAGING STEEL STRENGTH AND AGING .

Tabulation comparing strength and aging time at constant temperature.

TABLE 4 VARYING 0.2% YEILD STRENGTH WITH RESPECT TO VARYING AGING TIME . C350 .

Part of data from Viswanathan,1993 of C350		
Aging Time	**Aging Temp**	**0.2% Yeild strength**
2h	640°C	1414MPa
4h	640°C	1308MPa
6h	640°C	1211MPa

TABLE 5 VARYING 0.2% YEILD STRENGTH WITH RESPECT TO VARYING AGING TIME . C250 .

Part of data from Lee,2007 of C250.		
Aging Time	**Aging Temp**	**0.2% Yeild strength**
1h	480°C	1763MPa
3h	480°C	1956MPa
6h	480°C	1930MPa

IV.IMPORTANCE OF PRECIPITATING ELEMENTS, CO, MO, TI AND AL .

Co, Al and Ti/Mo ratio are determining factors in precipitation reaction and strengthening of the alloy.

Cobalt(Co): Cobalt promotes the precipitation hardening.

Molybdenum (Mo): The addition of Mo produces fine-grained steels, increases hardenability, and improves Fatigue strength. Pronounced carbide former Molybdenum can induce secondary hardening during the tempering of quenched steels[10].

Titanium (Ti): is a very strong carbide and nitride former. By the addition of Ti, intermetallic compounds are formed in maraging steels, causing age hardening [10].

V.ACTIVATION ENERGY REQUIREMENT (A E CONSTANT)

CONDITIONS FOR AE $_{CONSTANT}$ CALCULATIONS.

(1)Both Ti and Mo are carbide promoters and hardeners hence their ratio is taken.
(2)Co and Al have independent roles.
(3)Addition of, increased quantitative percentage of alloying elements thus ends up requiring increased activation energy for precipitation.

Calculating AE constant for C 350 ,all values taken from table II.
$Ti/Mo_{350\,C} + Co_{350C} + Al_{350C}$
1.63/3.99 + 12.32 0.12 = 12.84
$AE_{constant\ C350} = 12.84$

Calculating AE constant for C 250 ,all values taken from table III.
$Ti/Mo_{250\,C} + Co_{250C} + Al_{250C}$
0.50/4.90 + 8.60+0.15 = 8.85
$AE_{Constant\ C250} = 8.85$

Modifications enhance the precipitation hardenability providing higher strength levels and aging peaks, but increase the activation energy requirement for precipitation[4] .

From above calculations, Activation energy requirement for precipitation in C350 is, more compared to C250.

VI. ALLOYING ELEMENT VARIATION CONSTANT.(C_{AVE})

C_{AVE} is conceptualized to see if the variation of precipitating elements from the Nominal value can affects the mathematical modeling of these steels.

C_{AVE} is the sum of ratios, of the modulus of the difference of element percentage to the, nominal values of element percentage.

C_{AVE} = Modulus of (Ni C350Nominal –Ni C350)/NiC350Nominal+…..
Similarly for all alloying element. (Only Ni, Co, Mo, Ti, Al included)

$C_{AVE\ C350}$ = 0.30 ie the variation of wt% alloying element from nominal ,for C350 is 30% only

$C_{AVE\ C250}$ = 0.80 ie the variation of wt% alloying element from nominal ,for C250 is 80% .

VII. JUSTIFICATION FOR FINDING C_{AVE}

In the year 2011, Nageswara Rao. et .al published paper which enlightens us about importance of maintaining alloying element quantity percentage for better results.

According to him when the, Alloying elements quantitatively fall short .ie it is not sufficient to realize the strength levels specified in the same Standard (AMS 6512);[11] Thus alloying element percentage variation from the nominal or standard value is a parameter to be noted for the betterment of Research.

CALCULATING (R_{S-T}) AND (R_{t-T}) FOR FINDING (RD)

VIII. R_{S-T} and R_{t-T} Calculation for C-350

R_{S-T} =Strength temperature ratio ,
R_{t-T} =Time temperature ratio.
Ratio Difference = RD .

Table 6: R S-T and R t-T for C-350.

Strength -Temp ratio	Time – Temp ratio	Difference $R_{ST} - R_{t-T}$
2	0.18	1.82
2.21	0.37	1.84
1.89	0.56	1.33

Table 7: Time,strength and RD comparison

Time	Strength	RD
2h	1414MPa	1.82
4h	1308MPa	1.84
6h	1211MPa	1.33

With Aging time, R_D which increases up to 4h of aging and decreases at 6h of aging .

IX.R_{S-T} AND R_{T-T} CALCULATION FOR C-250

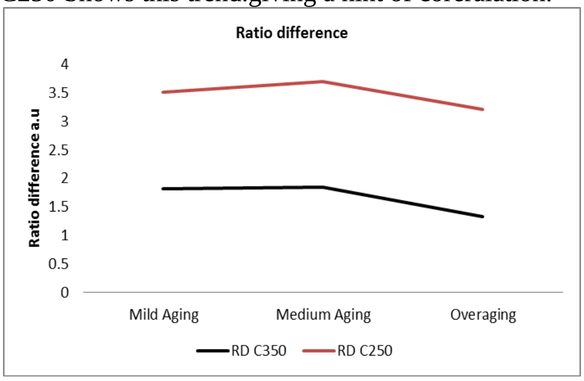
Table 8: Strength, Time and RD comparison for C-250

Strength -Temp ratio	Time – Temp ratio	Difference $R_{ST} - R_{t-T}$
3.67	0.12	3.5
4.07	0.37	3.7
4.02	0.75	3.2

Table 9: Time,strength and RD comparison

Time	Strength	RD
1h	1763MPa	3.5
3h	1956MPa	3.7
6h	1930MPa	3.2

With Aging time, RD which increases up to 3h of aging and decreases at 6h of aging .both C350 and C250 Shows this trend.giving a hint of coreralation.



The RD (Ratio difference) for both the grades of steel increases and the decreases despite aging temperature being different .this similarity in trend gives hope for comparative study of C250 and C350.

X.CONDITIONS FOR MATHEMATICAL MODELLING

(a)Austenite Reversion is neglected.
(b)Cold rolling and internal stress is neglected.

(c)0.2% Tensile Yeild is and aging time is at a constant aging temperature is considered.

(d)Calculation is only for finding consecutive aging time when Aging temperature is known and when data of one trial is available.

(e)One known trial will be ,$Temp_{known}$, $Time_{Known}$,0.2Yeild is $_{known}$

SL No	Equations and Symbols
01	Time x Temperature = Strengthening , is taken as the expression for ageing.
02	T 1 = Strength1 / temperature 1, T1 in hours , Strength in Mpa and temprature in Celcious
03	Equation for finding false ageing time (T2) , (T1)÷(T2) = (S1/t1) ÷ (S2/t2) t1 =t2 , constant temperature of ageing, T1 is actual ageing time for achieving Strength1.
04	Constant for parameter to which strength is indirectly-proportional;Cip=(temperature1/Strength1) ÷ (temperature2/Strength2) .
05	Constant for parameter to which strength is directly proportional;Cdp=(Strength1/temperature 1) ÷ (Strength2/temperature2). temperature 1 = temperature 2 , constant temperature at ageing process
06	Theoretical ageing time (To2) = T2 +Cip+Cdp
07	C_{AVE} is the sum of ratios, of the modulus of the difference of element percentage to the, nominal values of element percentage. C_{AVE} = Modulus of (Ni $_{C350}$Nominal –Ni $_{C350}$) ÷ (Ni$_{C350}$Nominal)+…..+

Considering **Case 1 for C 350** , finding theoretical ageing time To2 , assuming T2 to be Unknown. Strength1, 1414 Mpa , and ageing time T1 is 2 h, Required strength 2 . 1308 Mpa ,

>2/T2 = (640/1414) ÷ (640/1308)
>2/T2 = (1308) / (1414)
>T2 = (2 x 1414) / (1308) = 2.16
Theoretical aging time = To2 = T2 +Cip + Cdp
Cip = (640/1414) ÷ (640/1308)
Cip =0.45/0.48 = 0.93
Cdp = (1414/640) ÷ (1308 / 640)
Cdp = 2.2/2 = 1.1

Theoretical ageing time =2.16+0.93+1.1
Theoretical ageing time= 4.1 hours

Case 2 for C 350 , T3 is considered unknown , Strength 3 , 1211 MPa , Strength 2 = 1308 MPa ,T2 is 4 hours .
(4/T3) = (1308/640) ÷ (1211 /640)
(4/T3) = (1308 x 640) ÷(640 x 1211)
(4/T3) = (1308) /(1211)
T3 = (4 x 1211) /(1308)
T3 = (4844) /(1308) = 3.70 hours

3.70 hours is, False ageing time for attaining the strength of 1211 Mpa.
Theoretical ageing time (To3) = T3 + Cip + Cdp

Finding Cip & Cdp for To3 , which is required to attain 1211 Mpa strength.

Cdp = (1304/640) ÷ (1211/640)
Cdp = (1304 x640) ÷ (1211 x 640)
= (1304)/(1211) = 1.09

Cip = (640/1308) ÷ (640 /1211)
= (0.48) / (0.52) = 0.92

To3 = 3.70 + 1.09 + 0.92 = 5.71h
5.71 hours is close to 6h

Similarly evaluating C 250 .
T2 is assumed unknown , Strength 1 ,1763 Mpa for ageing period T1 , 1hour at constant ageing temperature 480 ^{o}C .

(1/T2) = (1763/480) ÷ (1956/480)
(1/T2) = (1763)/ (1956)
T2 = (1956) /(1763)

T2 = 1.10 hours is the false ageing time required to achieve the strength of 1956 Mpa.

To2 = T2 + Cdp + Cip
Cdp ,the constant for unknown parameter to which strength is directly proportional .

Cdp = (1763/480) ÷ (1956/480)
Cdp = 0.90

Cip = (480/1763) ÷ (480/1956)
Cip = = 1.12
To2 = 1.10 +0.90+1.12
To2 = 3.12 hours

3.12 h ,Theoretical ageing time that is required acquiring strength of 1956 MPa at 480 ^{o}C .

Now assuming T3 as unknown for C 250 steel ,T2 3hours , Strength 2 is 1956 Mpa and Strength 3 ,1930 Mpa which is considered required strength which can be achieved by ageing the material C250 in To3 hours at 480 ^{o}C . all C250 actual tensile test values were taken from Lee 2007 .

(3/T) = (1956/480) ÷(1930/480)
(3/T) = 4/4,
T3 = 12/4 = 3 hours . is the false ageing time required to achieve strength of 1930 MPa .

And (To3) = T3+Cdp + Cip
Cdp = (1956/480) ÷ (1930/480) = 4/4 = 1
Cip = (480/1956) ÷ (480/1930) = 1
To3 = 3 +1 +1 = 5 hours

Theoretical aging time To3 above for C250 ,lags by 1 hour .

Table :11 Actual time and Theoretical time comparison.Below results are of maraging steel C -250 heat treated at 480 ^{O}C and maraging steel C -350 heat treated at 640 ^{O}C .

SL No	Strength (MPa)	Time (h)	To (h)	Cdp (Constant)	Cip (Constant)	C_{AVE}	AE constant
1.C350	1308	4	4.10	1.1	0.93	30	12.85
2.C350	1211	6	5.71	1.0	0.92	30	12.85
3.C250	1956	3	3.12	0.90	1.12	80	8.85
4. C250	1930	6	5	1	1	80	8.85

Table :11 .1

	Time (h)	To (h)	Cdp (Constant)	Cip (Constant)	C_{AVE}	AE constant
(a)	4	4.10	1.1	0.93	30	12.85
(b)	6	5.71	1.0	0.92	30	12.85
(c)	3	3.12	0.90	1.12	80	8.85
(d)	6	5	1	1	80	8.85

Note:
1. Cip - Constant for unknown parameter which is indirectly proportional to strength.
2. Cdp - Constant for unknown parameter which is directly proportional to strength.
3. Cip and Cdp are opposing effects .
4. C_{AVE} - Value depicting the variation of % alloying elements from nominal values mentioned for that particular grade of maraging steel.
5. T, is the actual time of ageing and To is the theoretical time of ageing.

XI. OBSERVATIONS

Here are some observations from table 11.

a) Actual ageing time 4 hours and theoretical ageing time is 4.1hours for C350 heat treated at 640^{o} C, here Cip (0.93) is less than Cdp (1.1). Noted C_{AVE} is 30% .

b)Theoretical ageing time is 5.71 hours (5hours ,42min) for C350 heat treated at 640^{o} C and actual time of ageing is 6 hours, here Cip (0.92) is less than Cdp(1.0) .Noted C_{AVE} is 30% .

c)Actual and theoretical ageing time are 3hours and 3.1hours for C250 heat treated at 480^{o} C, here Cip (1.12) is more than Cdp (0.90) .Noted C_{AVE} is 80% .

d) Theoretical ageing time calculated is 5 hours , and Actual ageing time is 6 hours for C250 heat treated at 480^{o} C . Here both Cdp and Cip value is 1.Noted C_{AVE} is 80%.

XII. CONCLUSIONS

Successfully coined an equation from basic idea , and further modeled it, using test data taken from trusted research papers applicable for both C-250 and C-350. This equation could be used for finding consecutive ageing time required to achieve a particular value of strength.

Both C-250 and C-350 have given accurate ageing time for ageing process ,required to achieve particular strength values at 3 hours and four hours respectively .ie accurate ageing time prediction at low ageing period ≤ 4hours .

All the 3 cases (a) ,(b) and (c) mentioned in observation has Cip > Cdp that means a parameter which helps in strengthening and which is directly proportional to ageing temperature is active in cases where servity of ageing is less .

For material C250 case of 6 hours of ageing .Theoretical ageing time calculated is 5 hours . Here both Cdp and Cip value is 1.Noted C_{AVE} is 80% . It could be the effect of 80% percentage varriation of material composition from Nominal values combined with longer ageing period. which is giving low theoretical ageing time . Case of C-350 having aged at comparitively heigher temperature with 30% C_{AVE} , has given 5.71 hours theoretical ageing period which is close to 6 hours .

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