Analysis of Process Parameters during Quenching and Tempering Heat Treatment for SS431 Grade Martensitic Stainless Steel using JMAT Pro Software

[1]Sudhir B. Wagh, [2]Abhinandan B. Admuthe,
[1]Student[2]Assistant Professor,
[1]Mechanical Engineering Department,
[1]Walchand College of Engineering, Sangli, India

Abstract : The cycle control of heat treatments, on the quenching and tempering operation for martensitic stainless steel, is essential for improved material performance. The appropriate choice of heat treatment parameters, can lead an optimization on its mechanical properties. Also, it is noted that the chemical composition has a vital influence on the mechanical properties of the phases existing and hence a critical control over the chemical composition is important. Therefore, this paper aims to investigate the effects of variations in chemical composition, and austenitizing and tempering temperatures, on the microstructure and mechanical properties of SS431 steel in JMat pro simulation software.

***keywords* – Heat Treatment, JMat Pro, Quenching and Tempering.**

I. INTRODUCTION

Martensitic stainless steels are primarily ternary alloys of iron, chromium, and carbon that contain a martensitic crystal structure in the hardened condition. The basic grade, the 410 grade was invented by Harry Brearley in 1913.The progression of the basic 410 martensitic stainless steel grade to the various other grades(414,416,420,431) with the presence of additional alloying elements.In the basic composition, there is no nickel. They are hardenable by heat treatments, and are generally less corrosion resistant relative to the other classes of stainless steels. Excess carbides may be present to improve wear resistance while elements such as niobium, silicon, tungsten, and vanadium may be added to improve the tempering response after hardening. Small amounts of nickel may equally be added to improve corrosion resistance in some media and to enhance toughness. Sulfur or selenium is added to some grades to enhance machinability. Applications of martensitic stainless steels (MSS) are cutlery, surgical instruments, scissors, springs, valves, shafts, ball bearings, turbine equipment, and petrochemical equipments [1].

Quenching is the process of fastly cooling metal parts from the austenitizing temperature, from within the range of 815 to 1060 °C for stainless steel. Quenching heat treatment process used to improve the hardness of a metal. Rapid cooling of metal part is done by submerging it into a oil, brine or water. The resulting part will have improved hardness and strength. Tempering of steel is a method in which previously hardened or normalized steel is heated to a temperature below the lower critical temperature and cooled at a suitable rate, mainly to increase ductility and toughness, but also to increase the grain size of the matrix. Steels are tempered by reheating after hardening to obtain specific values of mechanical properties and also to relieve stresses and to ensure dimensional stability[2].

II. JMAT PRO

JMatPro is simulation software which calculates a wide range of materials properties for alloys and is particularly aimed at multi-component alloys used in industrial practice. Using JMatPro we can make calculations for

- Solidification behaviour and properties
  In this involve calculation of thermo-physical and physical property during solidification
- Mechanical properties
  In this involve calculation of hardness, strength, etc
- Thermo physical properties
  In this involve calculation for specific heat and enthalpy, density and thermal expansion coefficient, thermal conductivity, Poisson's ratio, etc
- Phase transformation.
  In this involve calculation for TTT/CCT/TTA diagrams, microstructure evolution and properties during heating, cooling and isothermal holding.

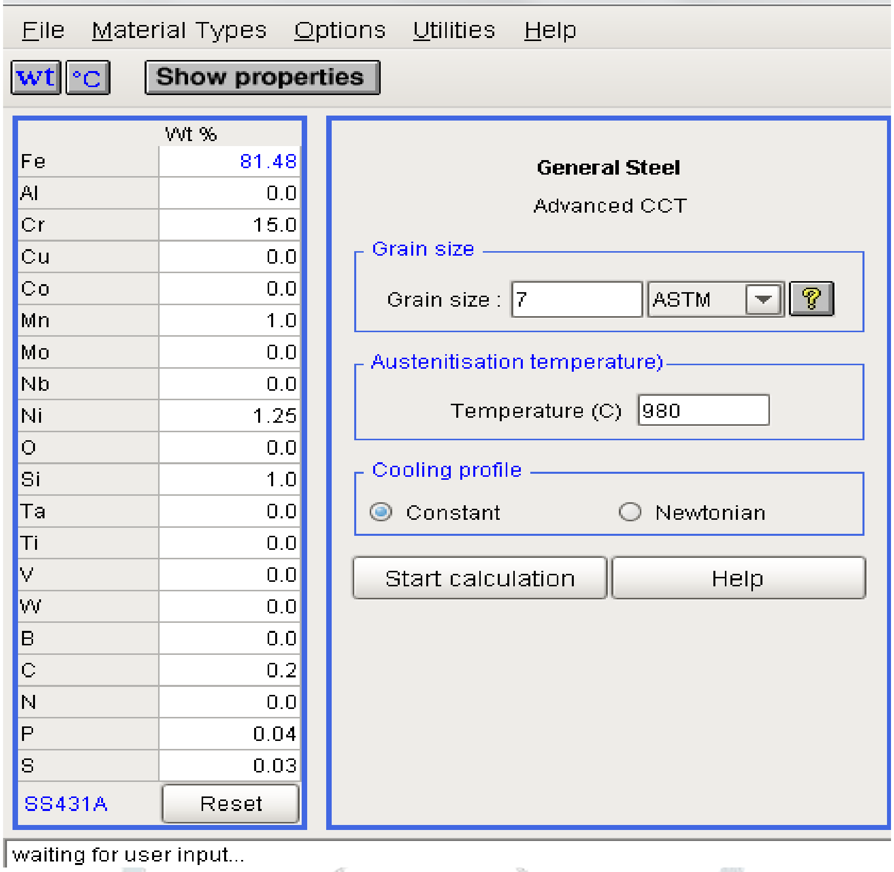
III. ANALYSIS OF PROCESS PARAMETERS

In process parameters we analyze two parameters austenitizing temperature and tempering temperature.

2.1 Austenitizing Temperature

Austenitizing is one of the heat treatment processes of steel and other ferrous alloys where these materials are heated above their critical temperatures long enough for transformations to take place. As per ASM Handbook Volume 4, austenitizing temperature range for SS431 grade is varying from 980ºC to 1065ºC. So from range taking three different temperatures that is 980 ºC, 1020 ºC and 1050 ºC as input for JMat pro to analyze at which temperature we get improved mechanical properties.

In JMat Pro simulation this analysis done in advanced CCT (continuous cooling transformation) property option as shown in following figure of JMat Pro input interface.



	Wt %
Fe	81.48
Al	0.0
Cr	15.0
Cu	0.0
Co	0.0
Mn	1.0
Mo	0.0
Nb	0.0
Ni	1.25
O	0.0
Si	1.0
Ta	0.0
Ti	0.0
V	0.0
W	0.0
B	0.0
C	0.2
N	0.0
P	0.04
S	0.03
SS431A	

General Steel

Advanced CCT

Grain size

Grain size : 7 ASTM

Austenitisation temperature)

Temperature (C) 980

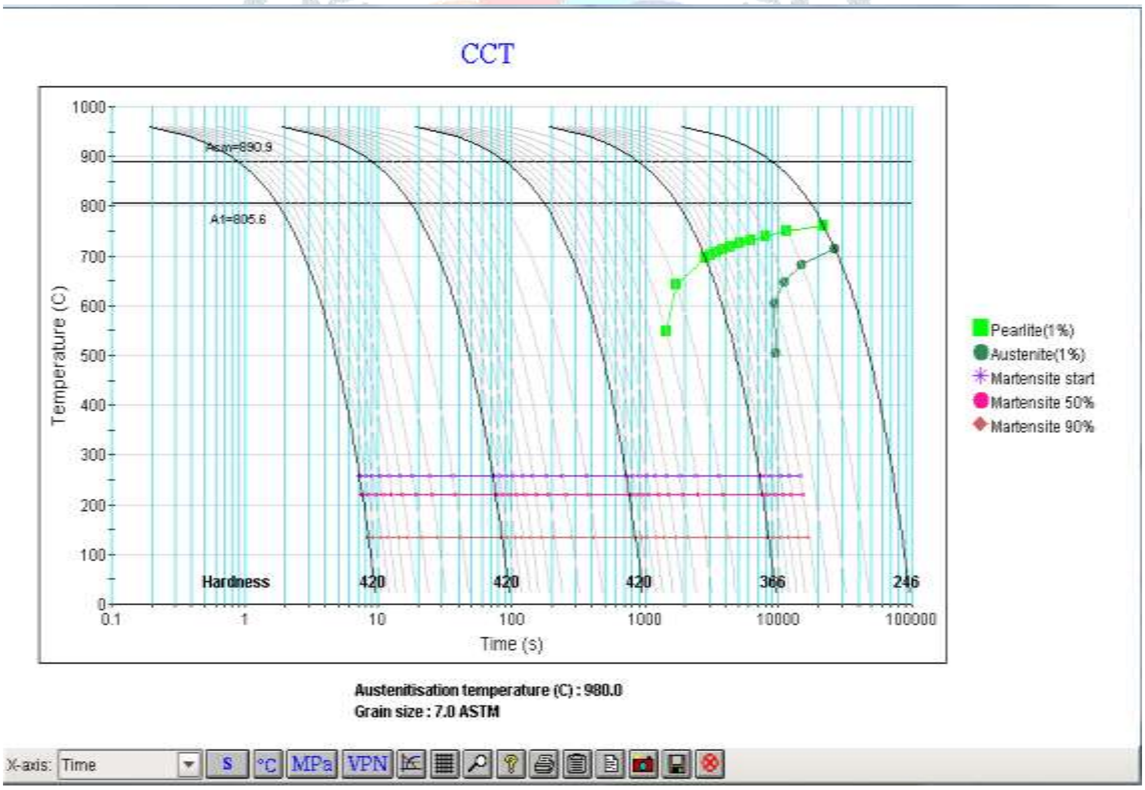
Cooling profile

● Constant ○ Newtonian

waiting for user input...

Fig 2.1 JMat Pro input interface for CCT calculations

As shown in above figure we give input as composition of SS431 grade and austenitizing temperature and go for calculation of continuous cooling transformation (CCT) diagram



Austenitisation temperature (C) : 980.0
Grain size : 7.0 ASTM

Fig 2.2 Continuous Cooling Transformation (CCT) diagram

Above CCT diagram shows lower cooling rate that is below 1 ºC /s we get majorly pearlite and ferrite microstructure, as cooling rate increases above 1 ºC /s we get martensite structure and small amount of pearlite. Overall result of CCT diagram mentioned in below table

Table 2.1: Overall Result of CCT Diagram

Cooling Rate (^{o}C /s)	Ferrite fraction	Pearlite fraction	Martensite fraction	Austenite fraction	Tensile Stress (MPa)
0.01	0	1	0	0	777.553
0.02	0	1	0	0	786.831
0.03	0	1	0	0	792.258
0.04	0	1	0	0	796.107
0.05	0	0.993996	0.005923	0	802.482
0.06	0	0.932932	0.066161	0.000906	839.125
0.07	0	0.80448	0.192877	0.002642	911.027
0.08	0	0.635779	0.359299	0.004922	1001.08
0.09	0	0.475776	0.517139	0.007084	1083.22
0.1	0	0.350145	0.641072	0.008782	1145.9
0.2	0	0.039797	0.947227	0.012975	1294.87
0.3	0	0.012458	0.974197	0.013345	1307.54
0.4	0	0.005666	0.980897	0.013437	1310.65
0.5	0	0.003301	0.98323	0.013469	1311.73
0.6	0	0.002067	0.984448	0.013485	1312.29
0.7	0	0.001426	0.98508	0.013494	1312.58
0.8	0	0.000996	0.985504	0.0135	1312.77
0.9	0	0.000783	0.985715	0.013503	1312.87
1	0	0.000615	0.98588	0.013505	1312.94
2	0	0.000104	0.986384	0.013512	1313.17
3	0	0	0.986439	0.013513	1313.17
4	0	0	0.986458	0.013513	1313.18
5	0	0	0.986466	0.013513	1313.19
6	0	0	0.986471	0.013513	1313.2
7	0	0	0.986474	0.013513	1313.2
8	0	0	0.986477	0.013513	1313.2
9	0	0	0.986478	0.013513	1313.21
10	0	0	0.986479	0.013513	1313.21

From above table it is observe that from cooling rate 1oC/S to 10oC/S we get martensite Structure above 90 percentage, therefore for next all combination we are taking constant cooling rate 10^{o}C/S and doing following calculations in quenched property option in JMat Pro.

As our focus is on martensite stainless steel we use constant 10 ^{o}C /S cooing rate for selected austenitizing temperature that is 980 ^{o}C, 1020 ^{o}C and 1050 ^{o}C and go for calculations

Table 2.2: Comparison at different autenitizing temperature

Hardness (VPN) at 980 ^{o}C	Hardness (VPN) at 1020 ^{o}C	Hardness (VPN) at 1050 ^{o}C
245.96	248.261	248.568
248.97	251.271	251.579
250.731	253.032	253.34
251.981	254.281	254.589
254.05	260.436	261.755
265.948	284.583	287.918
289.314	323.211	328.458
318.583	363.253	370.281
345.257	395.358	402.329
365.577	417.041	423.887
413.686	466.236	472.898
417.762	470.404	477.043

418.764	471.464	478.124
419.11	471.844	478.508
419.29	472.028	478.694
419.383	472.13	478.791
419.445	472.192	478.853
419.476	472.228	478.888
419.5	472.257	478.917
419.573	472.316	478.979

Table shows hardness values at different austenitizing temperature. From table it is observed that as austenitizing temperature increases hardness and other mechanical properties like tensile strength, yield strength get improved. As at 1050 °C temperature we get improved properties hence for all next calculation we take constant austenitizing temperature 1050 °C.

3.2 Tempering Temperature

Steels are tempered by reheating after hardening to obtain specific values of mechanical properties and also to relieve quenching stresses and to ensure dimensional stability.

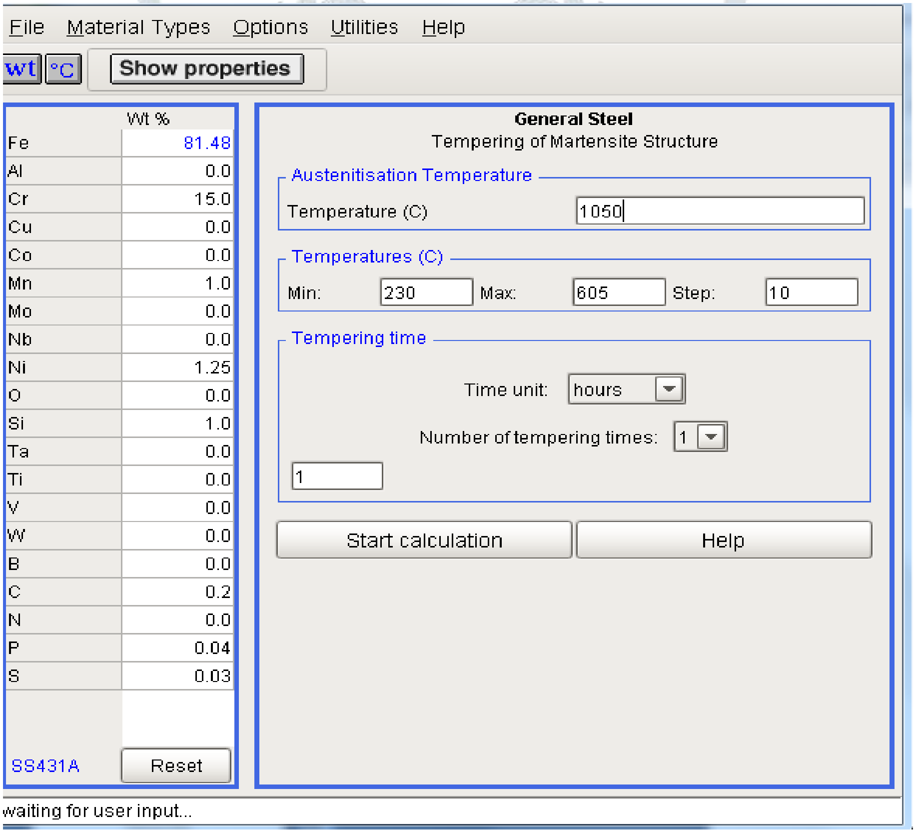
Tempering involves reheating the hardened martensite to a temperature between 230°C -605°C.

Tempering carried in 3 stages

i. Lower temperature tempering (230°C -370°C)
ii. Intermediate temperature tempering (370°C -565°C)
ii. High temperature tempering (565°C -605°C)

We give input parameters for tempering calculation on input interface of JMat pro as

Austenitizing Temperature	1050 °C
Tempering Range	230 °C -605 °C
Time	1 hour
Composition	C-0.2 Cr-15 Ni-1.25



	Wt %
Fe	81.48
Al	0.0
Cr	15.0
Cu	0.0
Co	0.0
Mn	1.0
Mo	0.0
Nb	0.0
Ni	1.25
O	0.0
Si	1.0
Ta	0.0
Ti	0.0
V	0.0
W	0.0
B	0.0
C	0.2
N	0.0
P	0.04
S	0.03

SS431A

General Steel
Tempering of Martensite Structure

Austenitisation Temperature
Temperature (C): 1050

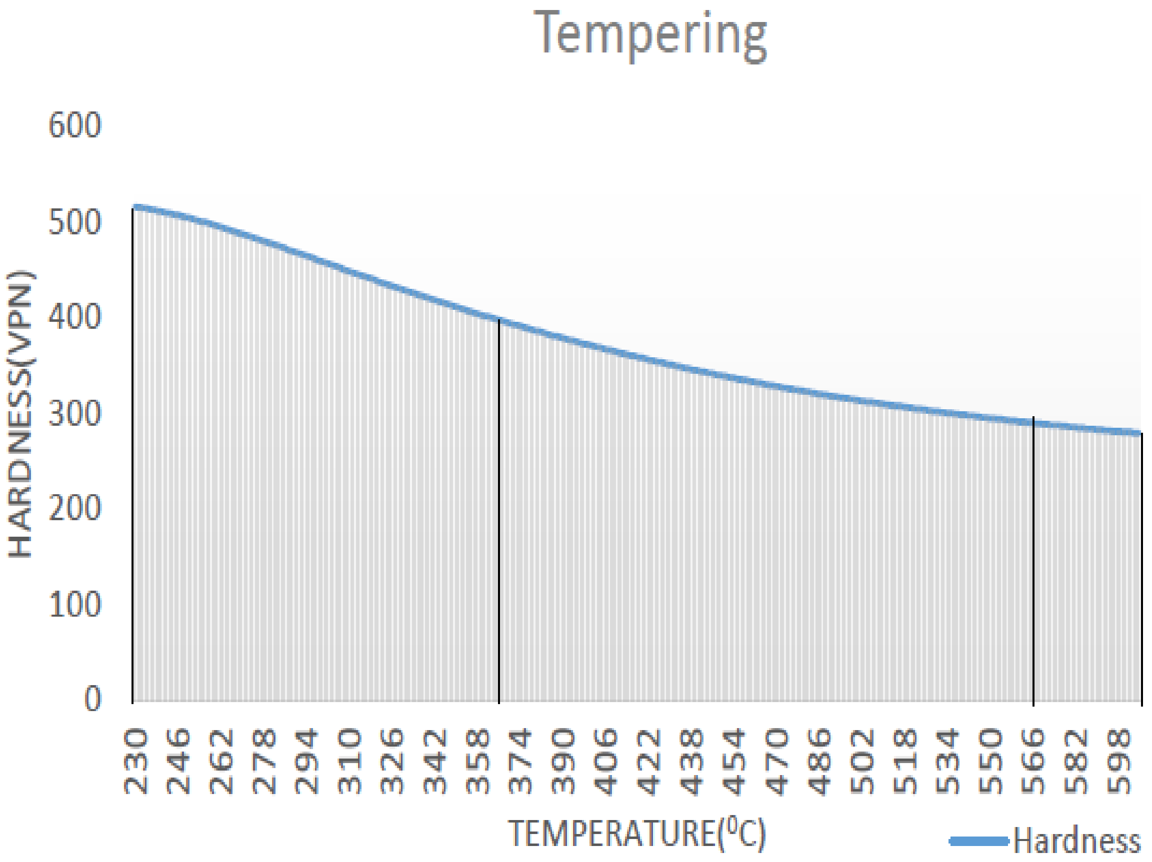
Temperatures (C)
Min: 230 Max: 605 Step: 10

Tempering time
Time unit: hours
Number of tempering times: 1
1

waiting for user input...

Fig 3.1 JMat Pro input interface for tempering calculations

After calculation we get following results



Graph 3.1 Effect of tempering temperature on hardness of SS431 MSS material

Graph shows as tempering temperature increases hardness values decreases. In high temperature tempering region that is from 565 °C to 605 °C hardness value decreases from (230 VPN to 310 VPN), while in low temperature tempering region that is from 230 °C to 370 °C hardness value increases from (420 VPN to 500 VPN)..

IV. ANALYSIS OF CHEMICAL COMPOSITION MODIFICATION

The composition of SS431 martensitic stainless steel grade in Wt.% as per ASTM A276 Standard is as follows

C	Mn	Si	Cr	Ni	P	S
Max 0.2	upto 1%	upto 1%	15%-17%	1.25%-2.5%	0.04%	0.03%

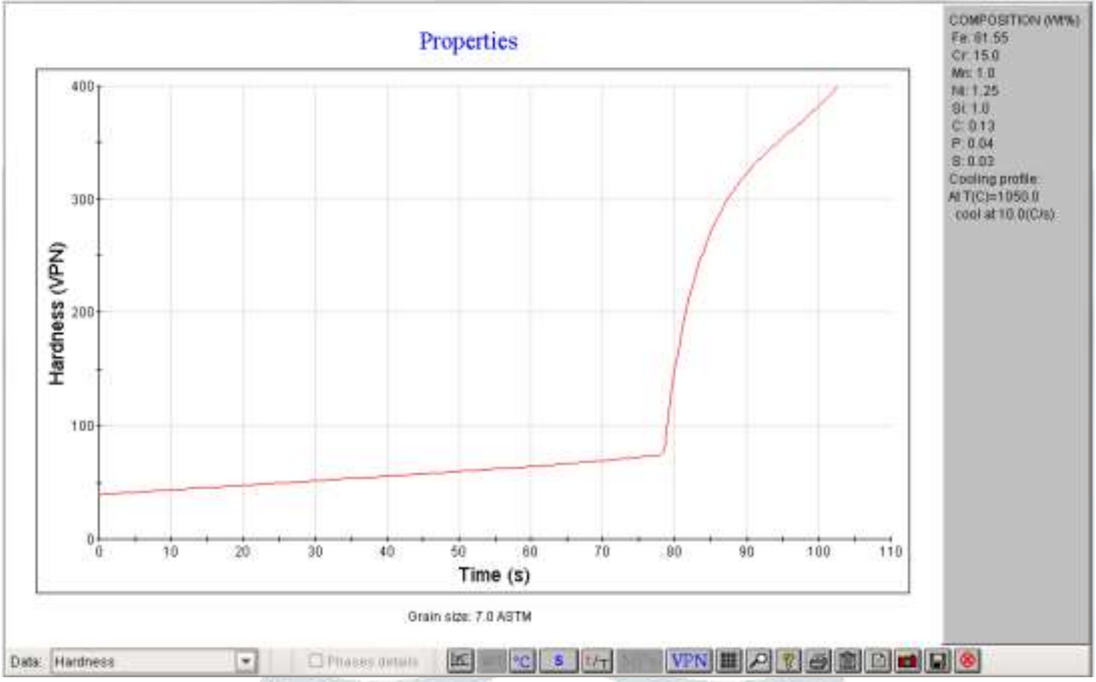
In this composition there are three major allying elements that are
i. Carbon (C)
ii. Chromium (Cr)
iii. Nickel (Ni)

So one by one varying each element by keeping other two constant, we can analyze how the mechanical properties changes. From CCT diagram we get that from cooling rate 1°C/S to 10°C/S we get martensite Structure, therefore for next all combination taking constant cooling rate 10°C/S and doing following calculations in quenched property option in JMat Pro

4.1 Carbon (C) variation during Quenching

4.1.1 At Carbon 0.13%

INPUT PARAMETERS	
Austenitizing Temperature (°C)	1050
Composition (Wt.%)	C-0.13 Cr-15 Ni-1.25



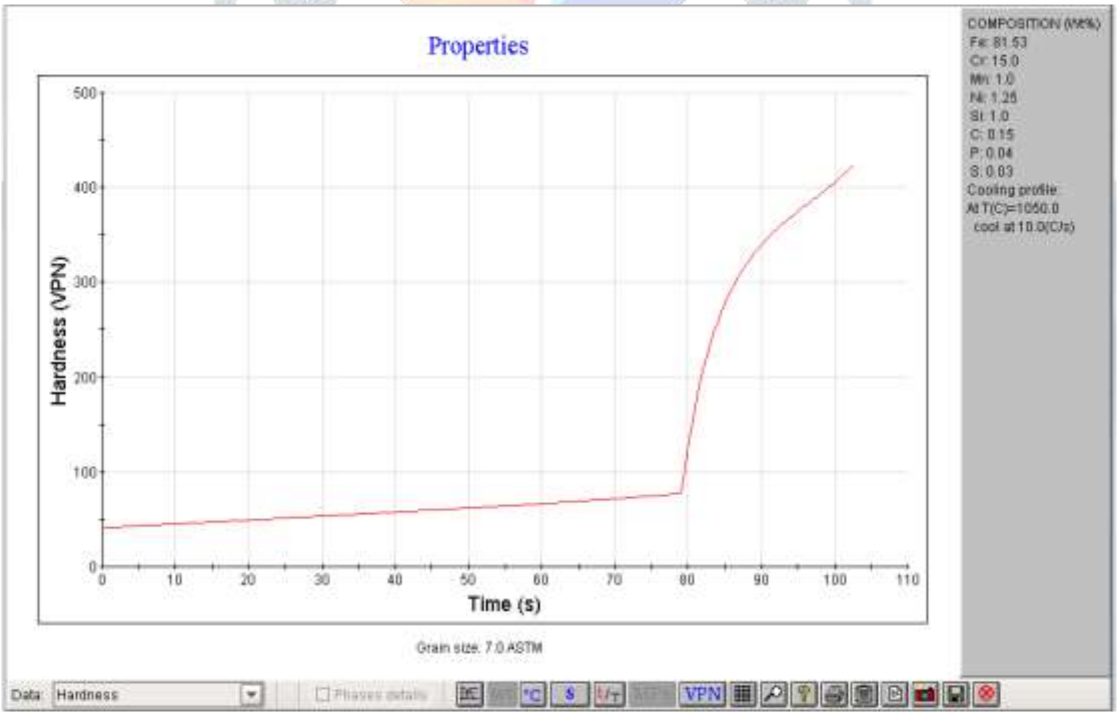
COMPOSITION (Wt%)
Fe: 81.55
Cr: 15.0
Mn: 1.0
Ni: 1.25
Si: 1.0
C: 0.13
P: 0.04
S: 0.03
Cooling profile:
At T(C)=1050.0
cool at 10.0(C/s)

Graph 4.1.1 Hardness at Carbon 0.13%

Graph shows Quenching time Vs. Hardness after quenching time 78 second austenite phase start converting into martensite structure and hardness value start increasing.

4.1.2 At Carbon 0.15 Wt %

INPUT PARAMETERS	
Austenitizing Temperature	1050
Composition (Wt.%)	C-0.15 Cr-15 Ni-1.25



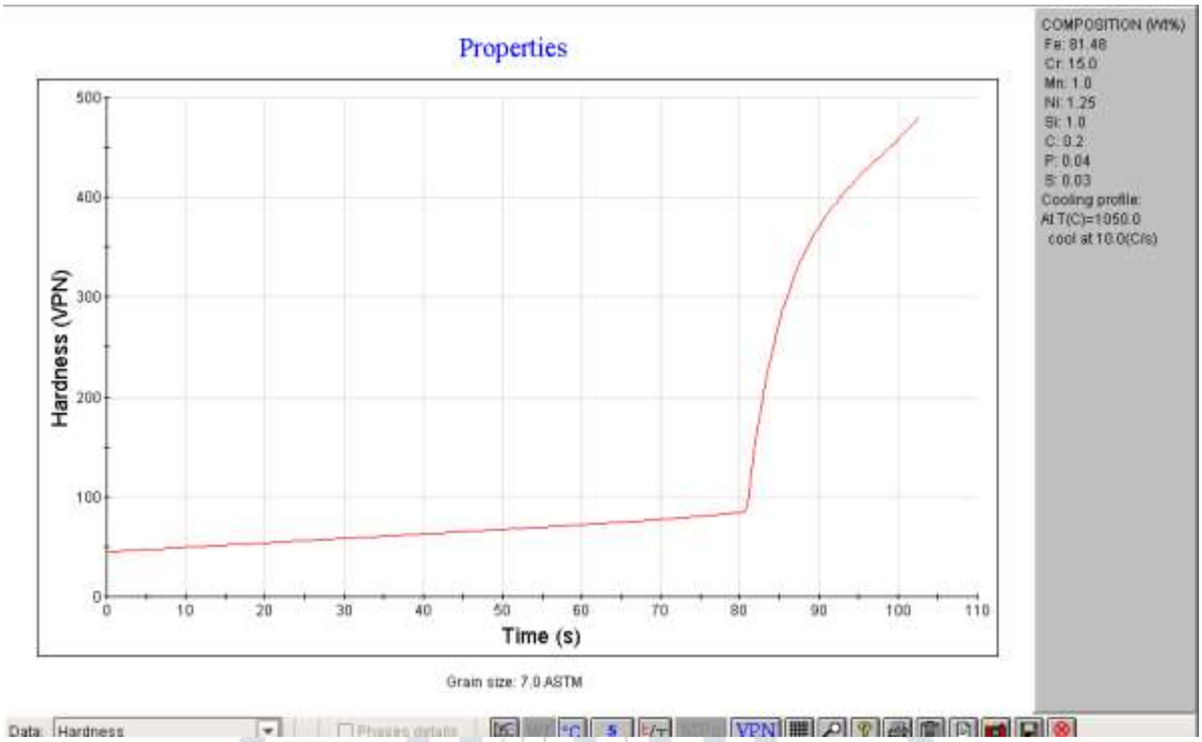
COMPOSITION (Wt%)
Fe: 81.53
Cr: 15.0
Mn: 1.0
Ni: 1.25
Si: 1.0
C: 0.15
P: 0.04
S: 0.03
Cooling profile:
At T(C)=1050.0
cool at 10.0(C/s)

Graph 4.1.2 Hardness at Carbon 0.15%

Graph shows Quenching time Vs. Hardness after quenching time 80 second austenite phase start converting into martensite structure and hardness value start increasing.

4.1.3 At Carbon 0.2%

INPUT PARAMETERS	
Austenitizing Temperature (ºC)	1050
Composition (Wt.%)	C-0.2 Cr-15 Ni-1.25



COMPOSITION (Wt%)
Fe: 81.48
Cr: 15.0
Mn: 1.0
Ni: 1.25
Si: 1.0
C: 0.2
P: 0.04
S: 0.03
Cooling profile:
At T(C)=1050.0
cool at 10.0(C/s)

Grain size: 7.0 ASTM

Graph 4.1.3 Hardness at Carbon 0.2%

Graph shows Quenching time Vs. Hardness after quenching time 83 second austenite phase start converting into martensite structure and hardness value start increasing. In this case hardness increases more as compare to previous two cases that is at carbon 0.13% and carbon 0.15%.

Conclusions for Carbon (C) Variations:

Table 4.1 Comparison of Carbon Variations

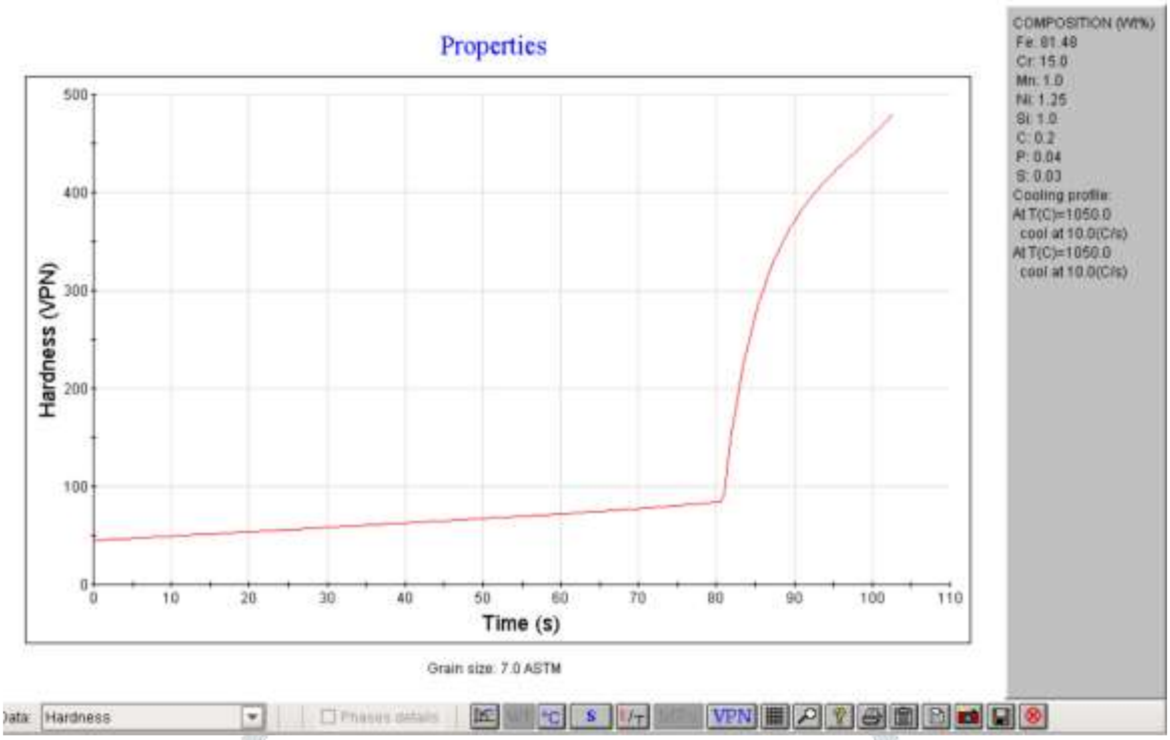
Variations (Wt.%)	M_s Temperature (°C)	M_f Temperature (°C)	Hardness in VPN
C-0.13	265	135	333
C-0.15	255	125	358
C-0.2	240	105	415

Above table show effect of variation in carbon on martensite start temperature (Ms), martensite finish temperatue (M_f) and hardness. From above table we can observed that as carbon percentage increases both martensite start temperature (Ms) as well as hardness increases.

4.2 Chromium (Cr) variations during quenching

4.2.1 At Cr 15%

INPUT PARAMETERS	
Austenitizing Temperature (°C)	1050
Composition (Wt.%)	C-0.2 Cr-15 Ni-1.25



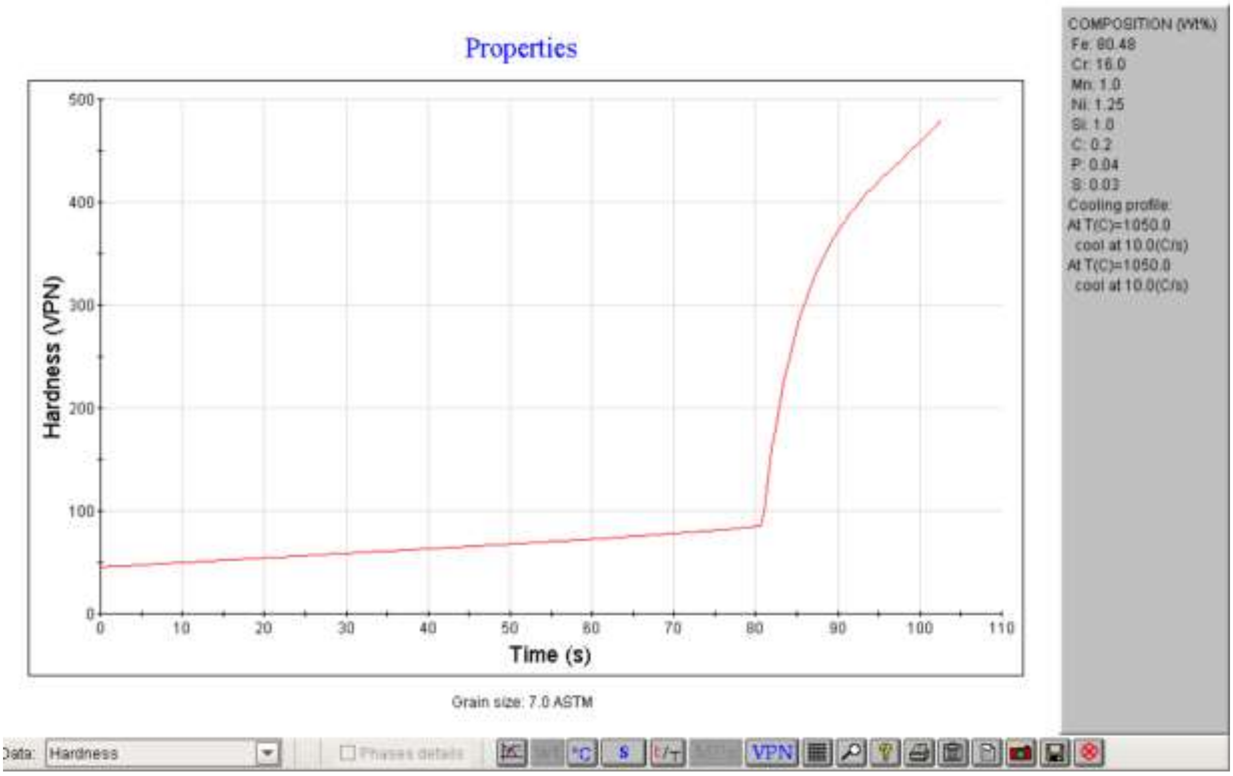
COMPOSITION (Wt%)
Fe: 81.48
Cr: 15.0
Mn: 1.0
Ni: 1.25
Si: 1.0
C: 0.2
P: 0.04
S: 0.03
Cooling profile:
At T(C)=1050.0
cool at 10.0(C/s)
At T(C)=1050.0
cool at 10.0(C/s)

Graph 4.2.1 Hardness at Chromium 15%

Graph shows Quenching time Vs. Hardness after quenching time 82 second austenite phase start converting into martensite structure and hardness value start increasing

4.2.2 At Cr 16%

INPUT PARAMETERS	
Austenitizing Temperature (ºC)	1050
Composition (Wt.%)	C-0.2 Cr-16 Ni-1.25



COMPOSITION (Wt%)
Fe: 80.48
Cr: 16.0
Mn: 1.0
Ni: 1.25
Si: 1.0
C: 0.2
P: 0.04
S: 0.03
Cooling profile:
At T(C)=1050.0
cool at 10.0(C/s)
At T(C)=1050.0
cool at 10.0(C/s)

Graph 4.2.2 Hardness at Chromium 16%

Graph shows Quenching time Vs. Hardness after quenching time 78 second austenite phase start converting into martensite structure and hardness value start increasing.

Conclusions for Chromium (Cr) Variation:

Table 4.2 Comparison of Chromium Variations

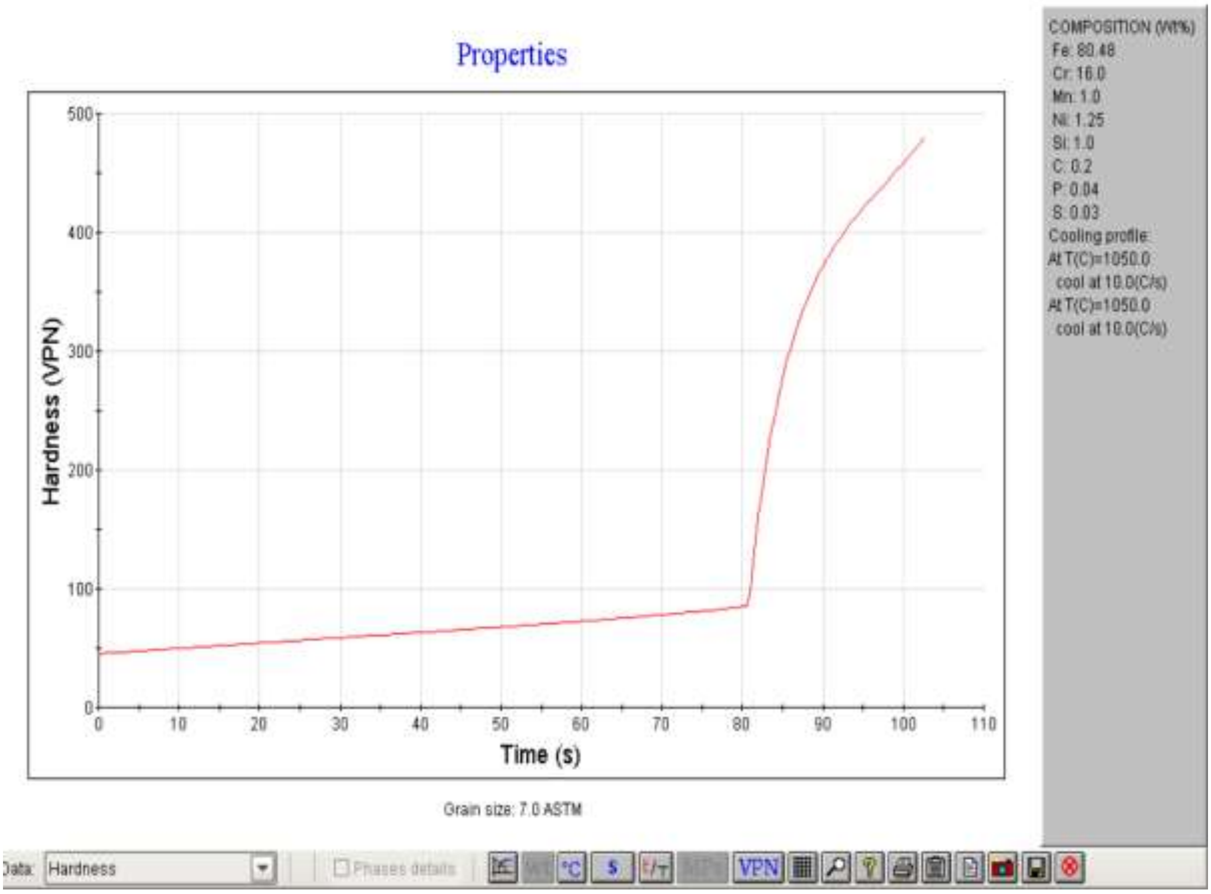
Variations (Wt.%)	M_s Temperature (°C)	M_f Temperature (°C)	Hardness in VPN
Cr-15	241	114	410
Cr-16	239	110	408

Above table show effect of variation in chromium on martensite start temperature (Ms), martensite finish temperatue (M_f) and hardness. From above table we can observed that as chromium percentage increases martensite start temperature decreases but hardness increases.

4.3 Nickel (Ni) Variations during quenching

4.3.1 At Ni-1.25%

INPUT PARAMETERS	
Austenitizing Temperature (°C)	1050
Composition (Wt.%)	C-0.2 Cr-16 Ni-1.25



COMPOSITION (Wt%)
Fe: 80.48
Cr: 16.0
Mn: 1.0
Ni: 1.25
Si: 1.0
C: 0.2
P: 0.04
S: 0.03
Cooling profile:
At T(C)=1050.0
cool at 10.0(C/s)
At T(C)=1050.0
cool at 10.0(C/s)

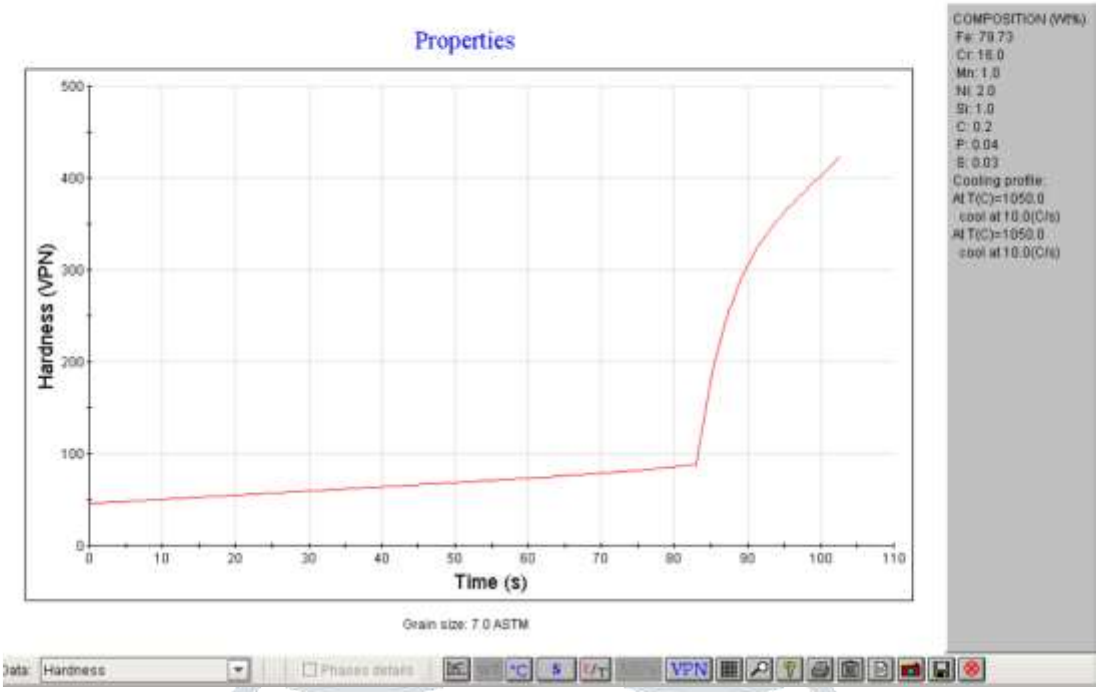
Grain size: 7.0 ASTM

Graph 4.3.1 Hardness at Nickel 1.25%

Graph shows Quenching time Vs. Hardness, after quenching time 82 second austenite phase start converting into martensite structure.

4.3.2 At Ni-2%

INPUT PARAMETERS	
Austenitizing Temperature (°C)	1050
Composition (Wt.%)	C-0.2 Cr-16 Ni-2



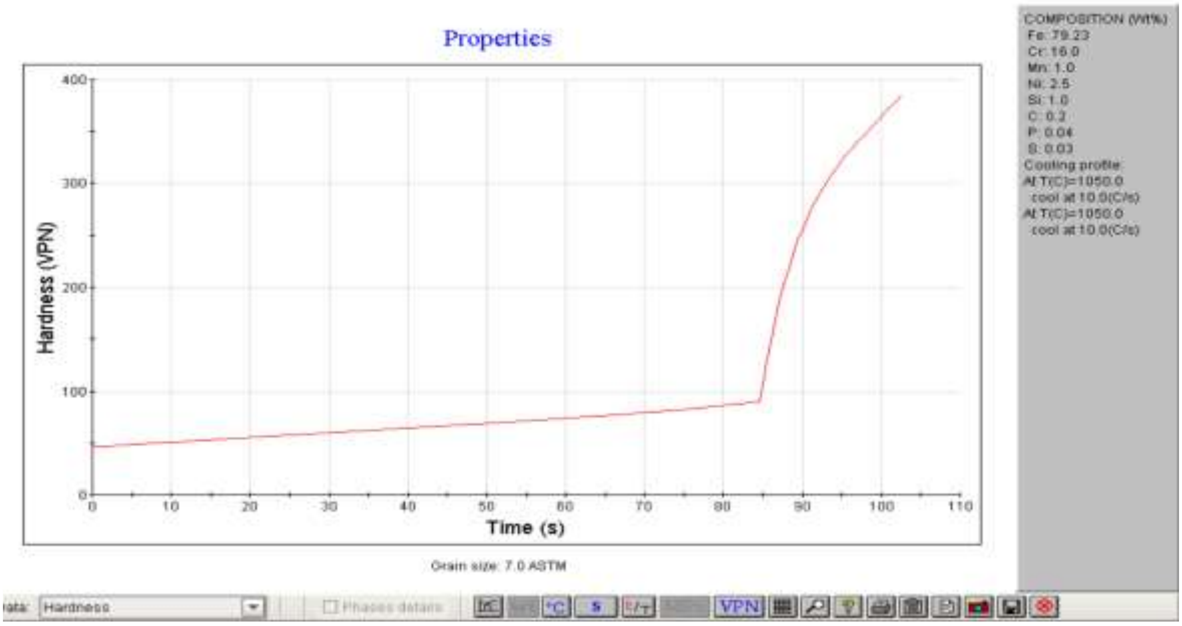
COMPOSITION (Wt%)
Fe: 79.73
Cr: 16.0
Mn: 1.0
Ni: 2.0
Si: 1.0
C: 0.2
P: 0.04
S: 0.03
Cooling profile:
At T(C)=1050.0
cool at 10.0(C/s)
At T(C)=1050.0
cool at 10.0(C/s)

Graph 4.3.2 Hardness at Nickel 2%

Graph shows Quenching time Vs. Hardness, after quenching time 84 second austenite phase start converting into martensite structure and hardness value start increasing.

4.3.3 At Ni-2.5%

INPUT PARAMETERS	
Austenitizing Temperature (°C)	1050
Composition (Wt.%)	C-0.2 Cr-16 Ni-2.5



COMPOSITION (Wt%)
Fe: 79.23
Cr: 16.0
Mn: 1.0
Ni: 2.5
Si: 1.0
C: 0.2
P: 0.04
S: 0.03
Cooling profile:
At T(C)=1050.0
cool at 10.0(C/s)
At T(C)=1050.0
cool at 10.0(C/s)

Graph 4.3.3 Hardness at Nickel 2.5%

Graph shows Quenching time Vs. Hardness after quenching time 78 second austenite phase start converting into martensite structure and hardness value start increasing.

Conclusions for Nickel (Ni) Variations

Table 4.3 Comparison of Nickel Variations

Variations (Wt.%)	M_s Temperature (°C)	M_f Temperature (°C)	Hardness in VPN
Ni-1.25	243	116	380

Ni-2	240	110	355
Ni-2.5	225	100	323

Above table show effect of variation in nickel on martensite start temperature (Ms), martensite finish temperatue (M_f) and hardness. From above table we can observed that as nickel percentage increases both martensite start temperature as well as hardness decreases.

V. CONCLUSIONS

Heat treatment parameters such as austenitizing temperature, tempering temperature and quenching medium (air and oil) play an important role. So by doing simulations we have analyze how the material behaves if these parameters changed in specific range. Also analyze the effect of major alloying elements carbon, chromium and nickel in the composition of SS431 grade of martensitic stainless steel on mechanical properties.

VI. REFERENCES

[1] WM GarrisonJr., Carnegie Mellon University, Pittsburgh,PA, USA MOH Amuda, University of Lagos,Lagos,Nigeriar "Stainless Steels:Martensitic" 2017 Elsevier.
[2] A.S.M. Handbook, Heat Treating, vol. 4, ASM International, Materials Park, OH, 1995
[3] A. Rajasekhar, "Heat Treatment Method applied to AISI 431 Martensitic Stainless Steel" J. Sci. Eng. Research 6 (4), 547–553 (2015).
[4] Sanusi K. O. and Akinlabi E. T. 2018 Experiment on Effect of heat treatment on mechanical and microstructure properties of AISI steel Materials Today: Proceedings 5 17996-18001
[5] Scheuer CJ, Fraga RA, Cardoso RP, Brunatto SF (2014) " Effects of heat treatment conditions on microstructure and mechanical properties of AISI 420 steel" 2014. J Alloy Compd 509:5857–5867
[6] L. F. ALVAREZ. C. GARCIAand V. LOPEZ "Continuous Cooling Transformation in Martensitic Stainless Steel" ISIJ International, Vol. 34 (1994), No, 6, pp. 516-521
[7] Saunders, N., Guo, U.K.Z., Li, X. et al. "Using JMatPro to model materials properties and behaviour". JOM 55, 60–65 (2003). https://doi.org/10.1007/s11837-003-0013-2
[8]ASTM A276 / A276M-17, Standard Specification for Stainless Steel Bars and Shapes, ASTM International, West Conshohocken, PA, 2017.