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Effect of Different Parameters of Quenching and Tempering Process on SS410 Grade Martensitic Stainless Steel

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Abstract: This paper reports the influence of different chemical composition, austenitizing temperature, quenching rate and tempering temperature on the mechanical properties and microstructure of martensitic stainless-steel SS 410 grade. For calculating general material properties such as hardness and yield strength of SS 410 grade, JMatpro software is used. Analysis of SS 410 grade has been done for austenitizing temperature ranging from 925^{0}C to 1010^{0}C followed by tempering whose temperature ranges from 205^{0}C to 605^{0}C.The proper practices of quenching and tempering should be performed ensuring the suitable microstructure of the steels. To get fully Martensite, quenching has to be done at least at 0.4^{0}C/s or more than that. The results also shows that composition of carbon has great effect on transition temperature M_s and M_f of martensitic stainless steel 410 grade as compared to chromium. Air cooling or oil quenching this type steels from austenite phase results in microstructure consists of mainly hard and brittle martensite, small amount of retained austenite. Subsequent tempering process reduces hardness and increases ductility and toughness.

Keywords: Martensitic stainless steel, SS Grade 410, JMatPro, Quenching, Tempering.

I. INTRODUCTION

Stainless steel is a group of iron-based alloys that contain a minimum of approximately 11% chromium, a composition that prevents the iron from rusting, as well as providing heat-resistant properties. There are numerous forms of stainless steel with varying chromium and other contents which mainly includes Austenitic, Ferritic, Duplex and Martensitic Stainless Steel. Among those, Martensitic stainless steels are basically ternary alloys of iron, chromium, and carbon that possess a martensitic crystal structure in the hardened condition. In the basic composition, there is no nickel. They are ferromagnetic, hardenable by heat treatments. Chromium in the steel is in the range of 10.5–18 wt. % with a higher level of carbon than the ferritic. These steels find extensive application in chemical plants, power generation equipment's, in gas turbines as turbine and compressor blades and discs. These steels can be heat treated to obtain a wide range of mechanical properties. This heat treatment process mainly includes annealing, quenching, tempering etc. Heat treatment processes are used to either soften or harden steel depending upon application. Annealing is softening process consisting of three stages heating, holding and cooling. Here cooling is done by switching off electric supply of furnace. In quenching, material is removed from furnace and submerged in agitated medium for cooling. Medium can be water, air or oil. On fast cooling, formation of martensite takes place. Tempering is heat treatment process with the help of which there is improvement in toughness and ductility while still maintaining strength level. Martensitic Stainless- Steel fall into different grades like SS410, SS414, SS403, SS416, SS420, SS440 etc. Among which grade 410 is general purpose grade and it is commonly used. Grade 410 Contains Chromium ranging from 11.5-13.5wt.%, Carbon ranging from 0.08-0.15 wt.%, Phosphorus is about 0.04wt.% and Sulphur is about 0.03 wt.%. As its Composition is moderate in nature, it has mild mechanical properties. It is useful in many applications including turbine blades, gate valves, Nuts, Bolts etc. Such applications need enhanced mechanical properties so that it can perform well in any environment. To improve those properties various heat treatment process like hardening, quenching, tempering etc. are being used.

II. SIMULATION IN JMATPRO

JMatPro is the practice tool for the calculation of temperature-dependent materials properties for a variety of technical alloys. It is increasingly used in Education and Research for the development or optimisation of material or technologies. It is also used for material data generation for CAE/FEM calculations. Following parameters can be studied in JMatPro-

1) Phase equilibria, phase transformations based on thermodynamics
2) Phase transformation and precipitation diagrams (TTT, CCT, TTP)
3) Mechanical-technological properties, e.g., strength, flow curves etc.

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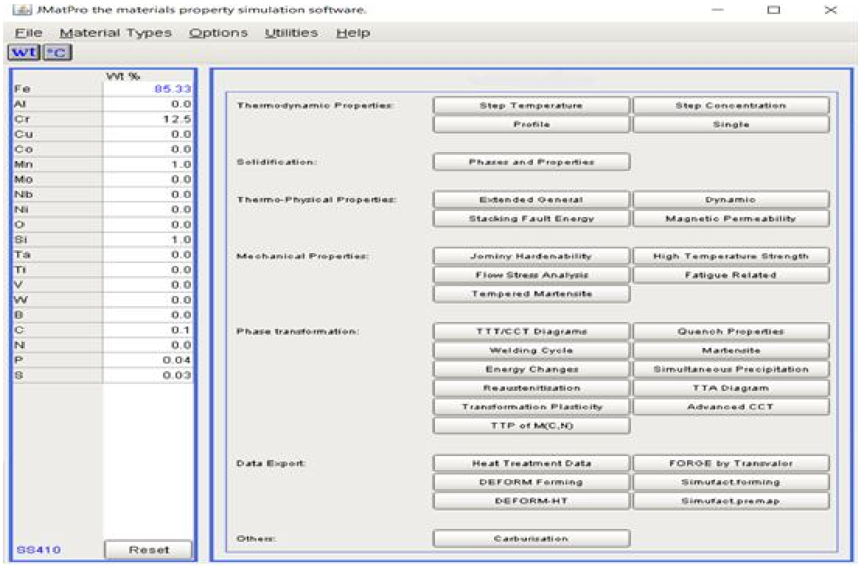

Fig.1 JMatPro Simulation Software Window

A. Phase Transformation and CCT Diagram

Continuous Cooling Diagram (CCT) provide valuable insights into the transformation that occurs in austenite when it is cooled at different cooling rates. Consequently, the heating parameters used will have a great effect on the transformations in the austenitic phase that occur during continuous cooling. Similarly, the cooling rate influences considerably the austenitic non-isothermal decompositions and transformation in the austenite process. Different cooling rates may cause different types of phases, which are produced by different formation mechanisms.

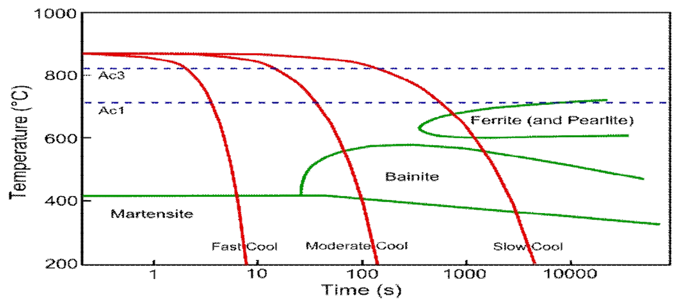

Fig:2 Continuous Cooling Transformation (CCT)

Heat treatment is a crucial step in the processing route of different types of steels. The precise control of heat treatment can improve the mechanical properties and microstructure. So good combination of varying parameters is required to achieve the desirable properties of SS 410 grade stainless steel. Following table gives the ranges for the varying parameters i.e., composition and temperature as per the ASTM standard.

Input Parameters	Low	Medium	High
Cr(wt.%)	11.5%	12.5%	13.5%
C(wt.%)	0.08%	0.10%	0.15%
Austenitizing Temperature(^{0}C)	925	970	1010
Tempering Temperature(^{0}C)	205-370	370-565	565-605

To perform simulation in JMatpro, above parameters have been used.

- *Results from Simulations:* During Continuous cooling transformation, SS410 grade having composition Cr-12.5% and C-0.15% shows better mechanical properties as compared to other at an austenitizing temperature 970^{0}C. Following table gives the hardness values for each composition.

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Table 4.3.3 Hardness VPN (HBW) values for Different Austenitizing Temperature

	925^0C	970^0C	1010^0C
When Cr-11.5%, C-0.15%	505.4(473)	514.3(482)	514.3(482)
When Cr-12.5%, C-0.15%	486.6(457)	514.4(482)	514.2(482)
When Cr-13.5%, C-0.15%	470.4(443)	514.3(481)	514.2(482)

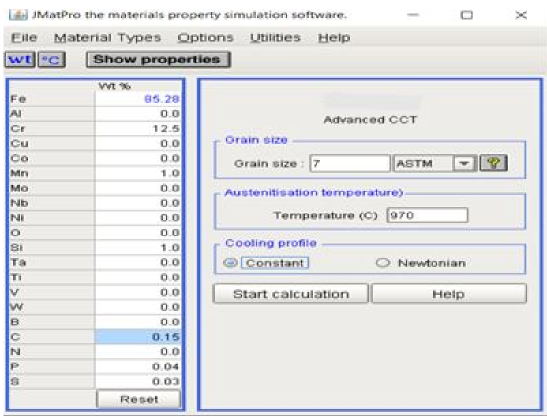

Fig.3:Input Parameter Window for CCT

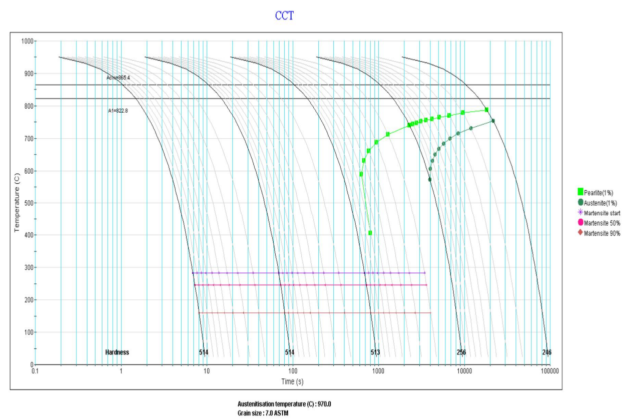

Fig.4: CCT diagram for austenitizing temp. at 970^0C

So, for further analysis, Cr-12.5%, C-0.15% and austenitizing temperature- 970^0c is used as a fixed parameter.

B. Quenching at Different Cooling Rate

Quenching is most commonly used process to harden steel by cooling workpiece in different environment. During quenching, phase transformation takes place depending upon different cooling rate. In accordance with different cooling rate, properties will change.

- Input Parameter: Cr-12.5%, C-0.15, Austenitizing Temperature-970^0C

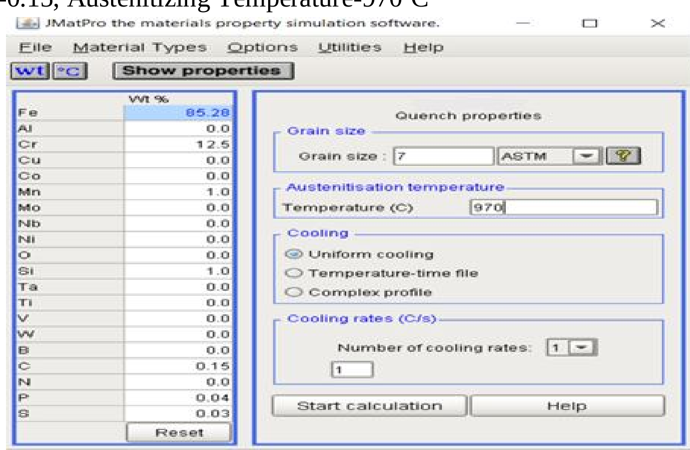

Fig.5 JMatPro Input Interface for calculating properties during quenching

➢ *Result from Simulation:* From the JMatPro simulation, we can conclude that to get martensite phase fully, cooling rate has to be 0.4^0C/s or more than that. When rate is within 0.01 up to 0.4^0C/s, there will be either Pearlite or Austenite. As soon as cooling rate varies from 0.1^0C/s to above, hardness increases significantly. When Cooling rate is about 0.4^0C/s, martensitic phase found in more extent and because of that hardness increases drastically.

1) Phase % for SS410 Grade:

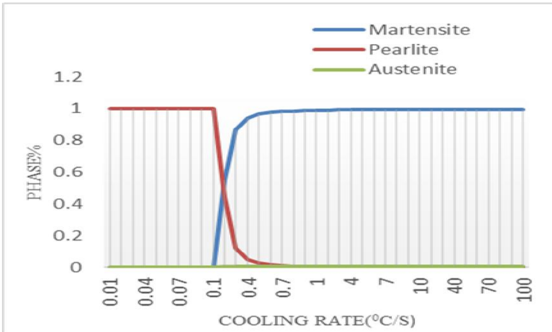

Fig.6 Graph of Cooling Rate(^{0}C/s) Vs. Phase%

2) Hardness Values:

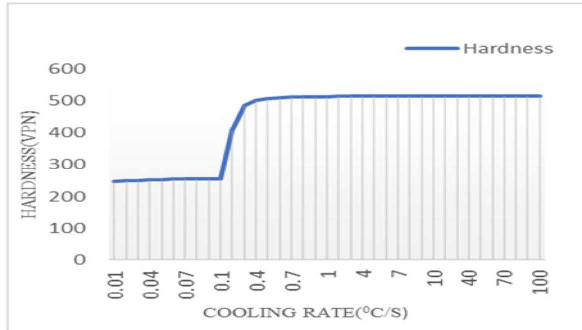

Fig.7 Graph of Cooling Rate Vs. Hardness

C. Properties After Quenching: Cooling Rate-10^{0}C/s:

During quenching, to get martensitic phase cooling rate has to be 0.4^{0}C/s or more than that. So, to analyze properties of SS 410 grade after quenching and tempering, Cooling rate has been taken as 10^{0}C/s.

1) For Different Carbon Variation

a) Input Parameters: C-0.08%, Cr-12.5%, Austenitizing Temperature-970^{0}C/s-

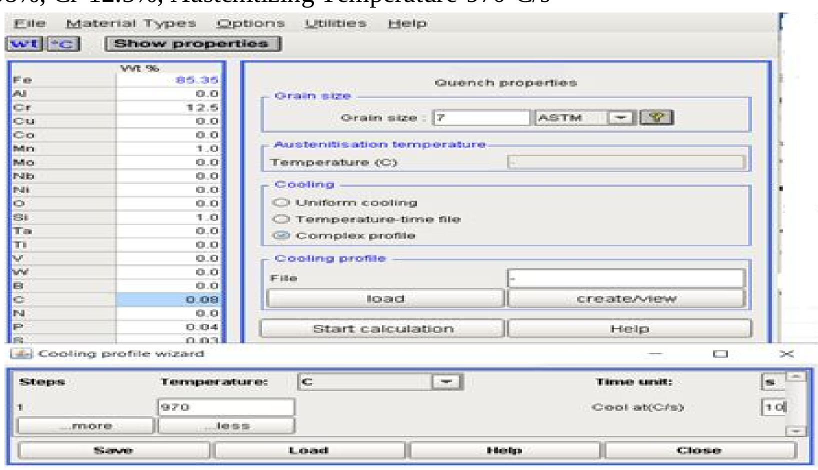

Fig.8 JMatPro Input Window for Calculating Properties after Quenching

➢ *Results:* From simulation: we can conclude that to get martensitic phase, quenching time has to be 65 seconds or more than that. When steel is quenched for less than 65 seconds hardness is comparatively low as austenite does not transformed into any other phase. As quenching time increases from 65 seconds and above, hardness increases abruptly because of evolution of martensite phase.

a) Phase%:

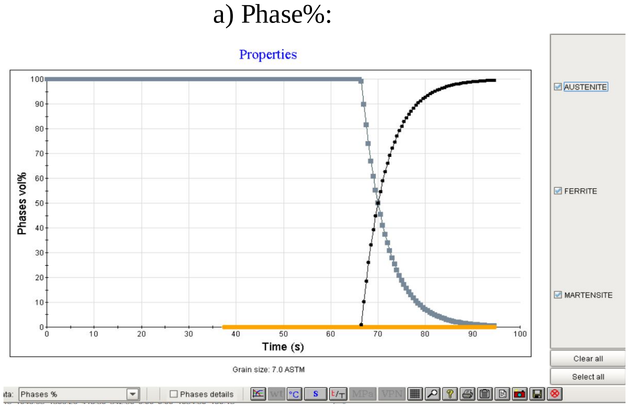

Fig.a) Graph of Quenching time Vs. Phase%

b) Hardness:

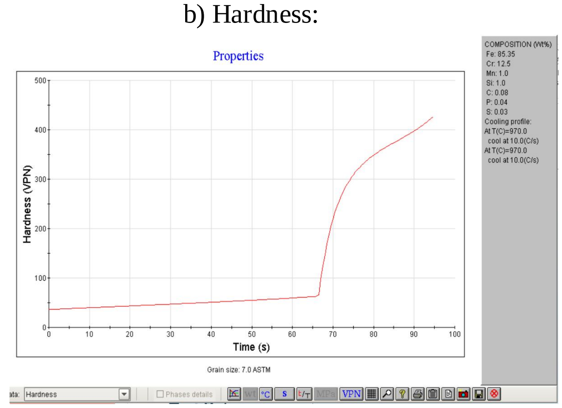

Fig.b) Graph of Quenching time Vs. Hardness

Quenching Time(s)	Phase (%)	Hardness (BHN)
up to 65	More Austenite	around 70 (70)
65 to 85	Austenite +Martensite	Increasing up to 380 (360)
after 90	More Martensite	Above 400 (379)

b) *Input Parameters:* C-0.10%, Cr-12.5%, Austenitizing Temperature-970^{0}C-

a) Phase%:

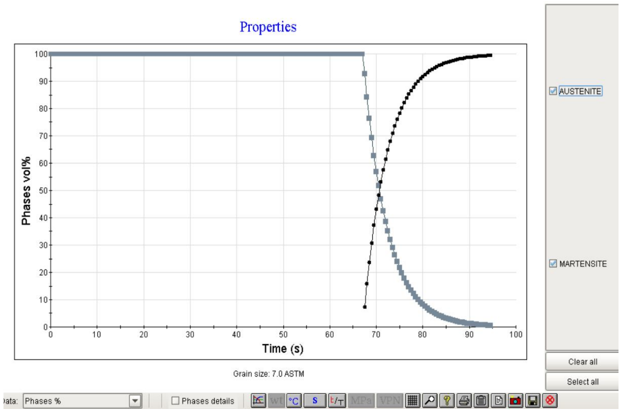

Fig.a) Graph of Quenching time Vs. Phase%

b) Hardness:

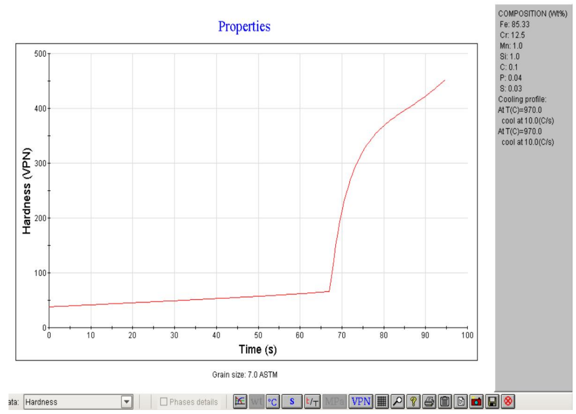

Fig.b) Graph of Quenching time Vs. Hardness

- *Results:* As the carbon wt. percentage increases from 0.08 to 0.10%, quenching time increases slightly. To get full martensite phase, quenching time has to be 95 seconds or more. As the carbon wt. percentage increases hardness value also increases as evolution of martensite phase takes place.

Quenching Time(s)	Phase (%)	Hardness VPN (HBW)
Up to 68	More Austenite	around 80 (80)
68 to 85	Austenite +Martensite	Increasing from 80 (80) to 400 (379)
After 95	More Martensite	Above 450

c) *Input Parameters:* C-0.15%, Cr-12.5%, Austenitizing Temperature-970^{0}C-

a) Phase%:

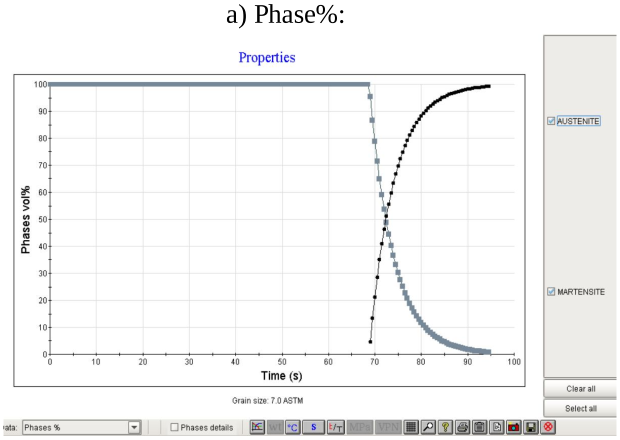

Fig.a) Graph of Quenching time Vs. Phase%

b) Hardness:

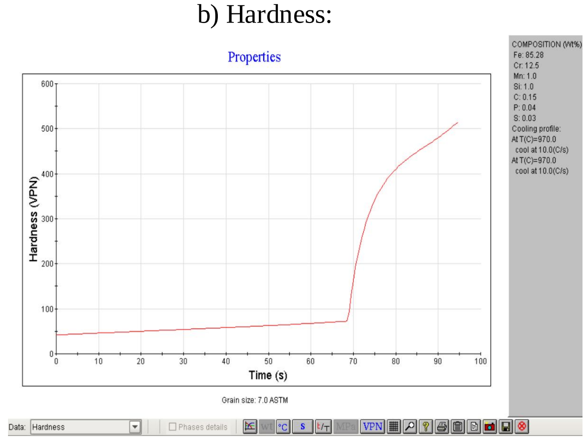

Fig.b) Graph of Quenching time Vs. Hardness

- *Results From Simulation:* For carbon weight percentage as 0.15%, quenching time required to start formation of martensite phase increases. Along with that, material gets more harder as carbon composition increases for same quenching time.

Quenching Time(s)	Phase (%)	Hardness (HBW)
Up to 70	More Austenite	100 (100)
70 to 85	Austenite+ Martensite	100(100) to 450(425)
Above 95	More Martensite	Above 500 (475)

2) *For Different Chromium Variation:* Similar to carbon variation, properties of SS 410 grade have been also studied for chromium variation ranges from Low (Cr-11.5%), Medium (Cr-12.5%) and High (13.5%) during quenching.

Quenching time	Phase%	Hardness (HBW)
around 70 sec	Only Austenite phase found	around 90 (90)
after 90 sec	Full martensite starts to form	above 500 (471)

a) Phase%:

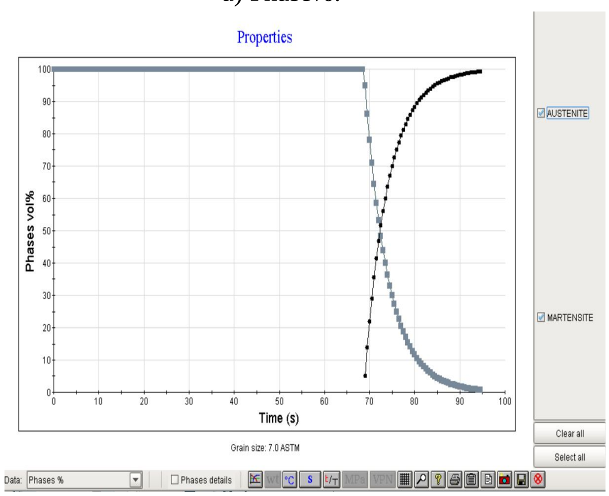

Fig.a) Graph of Quenching time Vs. Phase%

b) Hardness:

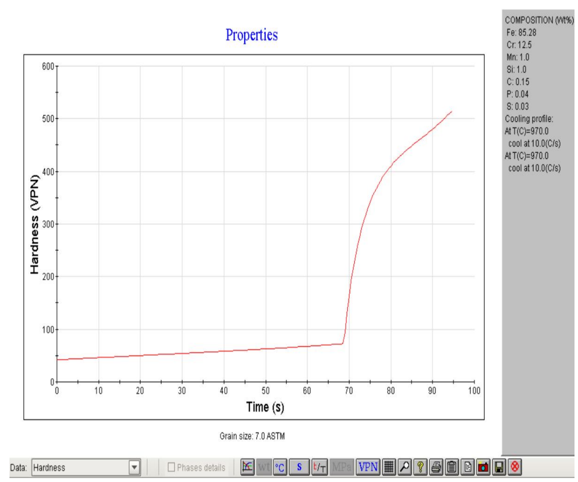

Fig.b) Graph of Quenching time Vs. Hardness

(Same Graph of for SS 410 grade having Cr-11.5%, Cr-12.5% and Cr-13.5% respectively)

Graphical Representation for Phase% and hardness Values for various Chromium weight percentage shows that there is no significant effect of it on SS 410 Grade bar. But for small change in carbon weight percentage, there is significant change in hardness values.

Table: Significance of Composition variation in Martensite Transition temperature

	Carbon variation Wt.%		
	C-0.08%	C-0.10%	C-0.15%
M_s (Martensite Start Temperature, ^{0}C)	305^{0}C	285^{0}C	280^{0}C
M_f (Martensite Finish Temperature, ^{0}C)	185^{0}C	175^{0}C	160^{0}C

	Chromium variation Wt.%		
	Cr-11.5%	Cr-12.5%	Cr-13.5%
M_s (Martensite Start Temperature, ^{0}C)	95.227	96.3	107.596
M_f (Martensite Finish Temperature, ^{0}C)	419.396	419.4	420.586

Discussions from above tables:

- Above table shows that carbon variation shows more impact on Martensite formation during quenching as compared to chromium variation.
  - As Carbon increases from 0.08% to 0.15%, Martensitic start temperature (M_s)and Martensitic Finish temperature (M_f) decreases i.e. we need to cool workpiece for more time to get martensitic
  - As Chromium weight percentage changes, no significant change occur on M_s and M_f
- Following is the Empirical relation for martensitic start temperature-

...….. (From ASTM Volume Handbook)

$$\mathbf{M_s(°C) = 512\text{-}453C\text{-}16.9Ni + 15Cr\text{-}9.5Mo + 217(C)^2 \text{-}71.5(C)(Mn)\text{-}67.6(C)(Cr)}$$

where, all above alloying elements are represented by their weight percentage.

Above relation shows that there is more Significance of Carbon weight percentage on Martensitic Start temperature. This validate the analytical results through simulation to the theoretical one.

D. Properties After Tempering

Tempering is process of heat treating which is used to increase toughness by decreasing toughness. It is performed after quenching. Reduction in hardness is accompanied by increase in ductility. This behavior of SS 410 grade over different carbon variation and temperature is analysed for tempering heat treatment by using simulation in JMatpro.

Calculation for Tempering time:

In case of cylindrical bar, general thumb rule is for one inch of radius, one hour is sufficient for transformation.

For experimentation, Dimensions of SS 410 cylindrical bar will be: Diameter- 40mm, Length-100mm

- For 20 mm radius, tempering time will be approximately 47 minutes.

1) For Carbon Variation:

Input Parameters: C-0.08%, Tempering temperature-205^{0}C to 605^{0}C, time-47 minutes

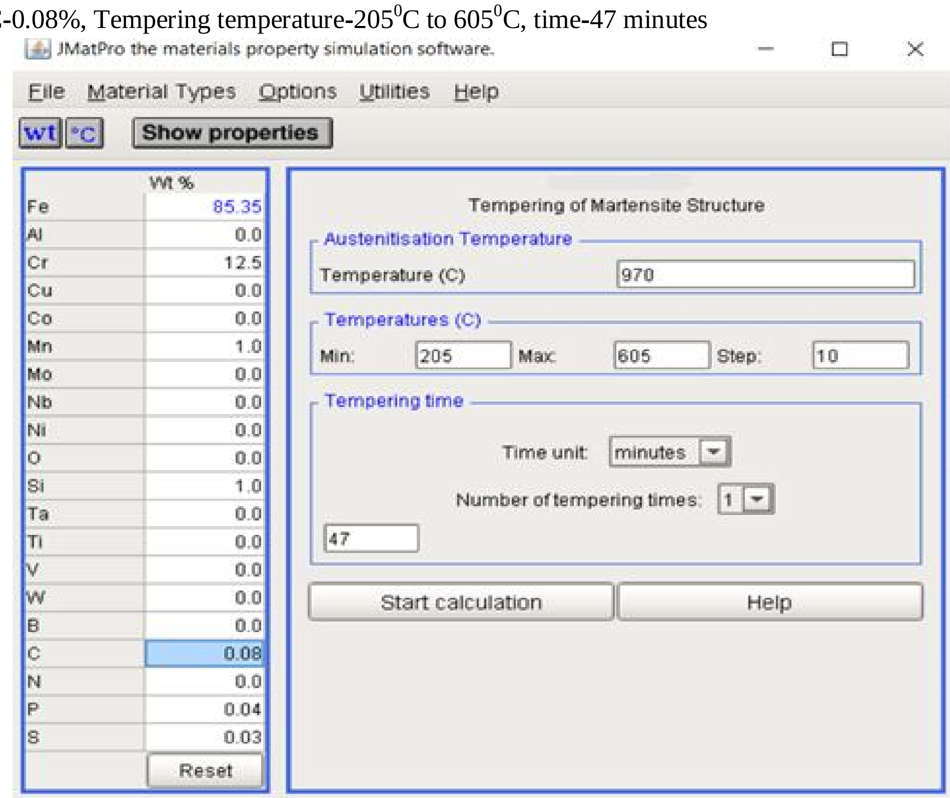

Fig.9 JMatPro Input Window for calculating properties after Tempering

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➢ *Results from Simulation*

- Hardness and Yield Strength variation of SS 410 having C=0.08%:

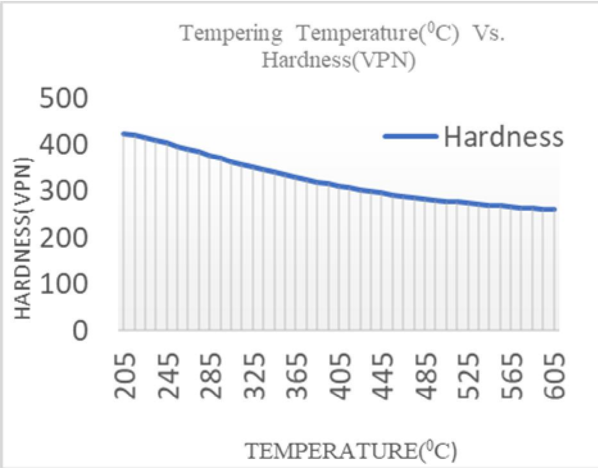


fig.a) Graph for tempering temp.Vs. Hardness

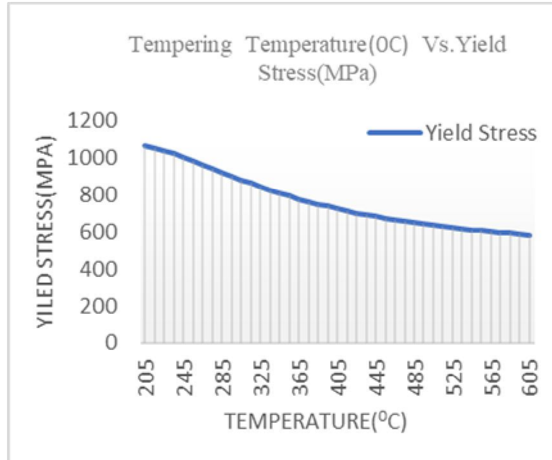


fig.b) Graph for tempering temp. Vs.Yield Stress

Tempering Temperature	Hardness (VPN)	Yield Stress (MPa)
205 to 370(^{0}C)	423 to 320	1067 to 785
370 to 565(^{0}C)	320 to 266	785 to 600
565 to 605(^{0}C)	266 to 260	600 to 583

- Hardness and Yield Strength variation of SS 410 having C=0.10%:

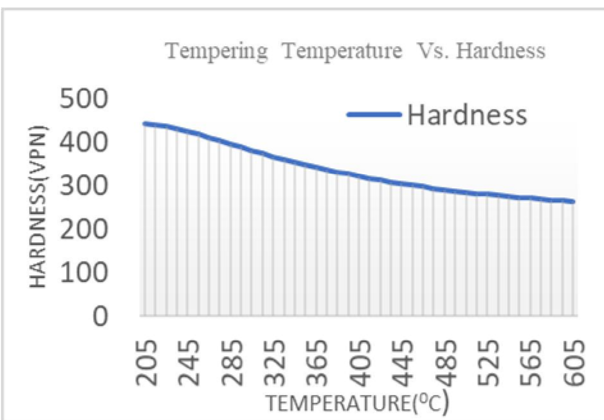


Fig. Graph for tempering temp.Vs. Hardness

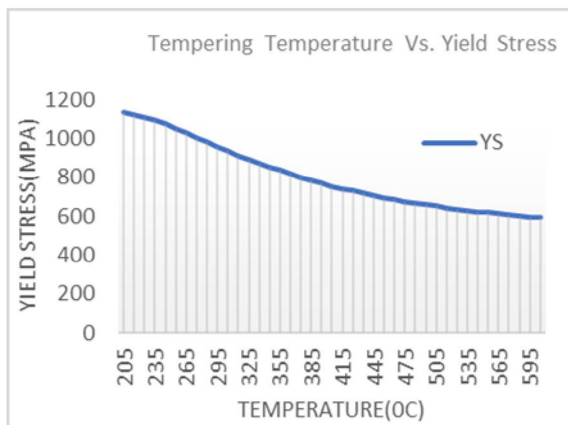


Fig. Graph for tempering temp. Vs.Yield Stress

Tempering Temperature	Hardness (VPN)	Yield Stress (MPa)
205 to 370(^{0}C)	444 to 340	1135 to 810
370 to 565(^{0}C)	340 to 271	810 to 612
565 to 605(^{0}C)	271 to 263	612 to 592

- Hardness and Yield Strength variation of SS 410 having C=0.15%:

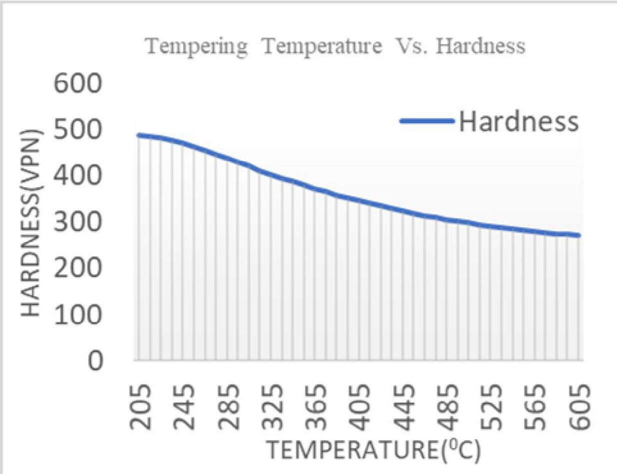


Fig. Graph for tempering temp.Vs. Hardness

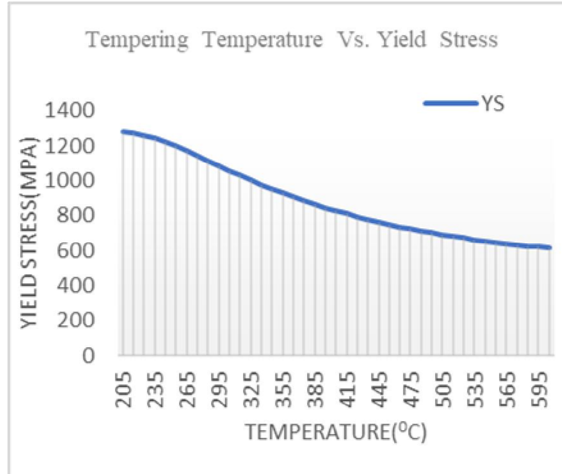
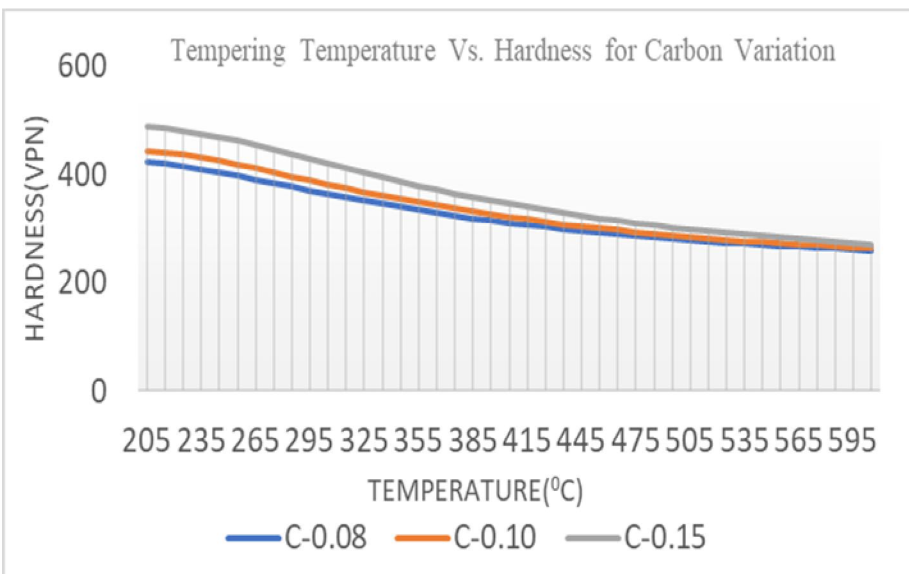


fig. Graph for tempering temp. Vs.Yield Stress

Tempering Temperature	Hardness (VPN)	Yield Stress (MPa)
205 to 370(^{0}C)	488 to 369	1279 to 894
370 to 565(^{0}C)	369 to 281	894 to 639
565 to 605(^{0}C)	281 to 271	639 to 614

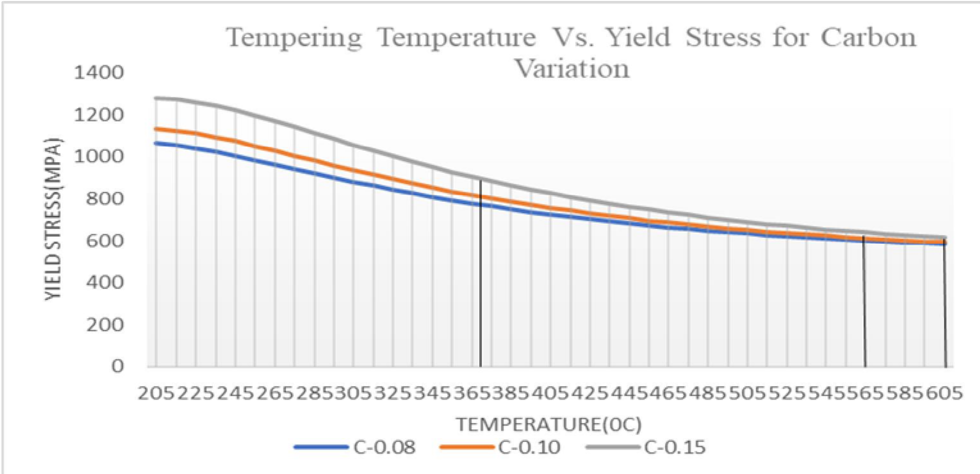
Comparison between Hardness for different C %:



(a) Graph of Tempering Temp. Vs. Hardness (VPN) for Carbon Variation

- *Results:* Above graph shows the hardness values for various carbon composition comparatively
- For Composition having C-0.15% has the better hardness property as compared to other carbon composition.
- Degree of Reduction of hardness for the composition having C-0.15% is more as compared to other carbon percentage.

Comparison between Yield Stress for different C %:



(b) Graph of Tempering Temperature Vs. Yield Stress for Carbon Variation

- *Results:* Above graph shows the Yield Stress value for Various carbon Composition Comparatively
- For Composition having C-0.15% has the better Yield Stress property as compared to other carbon composition.
- Degree of Reduction of Yield Stress for the composition having C-0.15% is more as compared to other carbon percentage.

III. DISCUSSION AND CONCLUSION

A. The influence of chemical composition, austenitizing temperature, quenching time and tempering temperature on the mechanical properties and microstructure of 410 martensitic stainless steel has been investigated. Above results shows that at austenitizing temperature 970^{0}C, SS 410 grade shows better mechanical properties.

B. To get fully martensitic phase, quenching rate of SS 410 grade has to be at least 0.4^{0}C/s or more than that. If rate is below 0.4^{0}C/s, we get either ferrite or more austenite.

C. As Carbon increases from 0.08% to 0.15%, transition temperatures Martensitic start temperature (M_s)and Martensitic Finish temperature (M_f) decreases i.e., we need to cool workpiece for more time to get martensitic. As Chromium weight percentage changes, no significant change occur on M_s and M_f unlike carbon weight percentage variation.

D. As tempering temperature increases from 205^{0}C to 605^{0}C, hardness and yield strength of SS 410 grade reduces. Effect of tempering temperature with carbon variation on mechanical properties of SS 410 grade is also studied by using JMatPro. Simulation shows that SS 410 grade having carbon 0.15wt. % shows better hardness and yield srength as compared to other composition.

IV. ACKNOWLEDGEMENT

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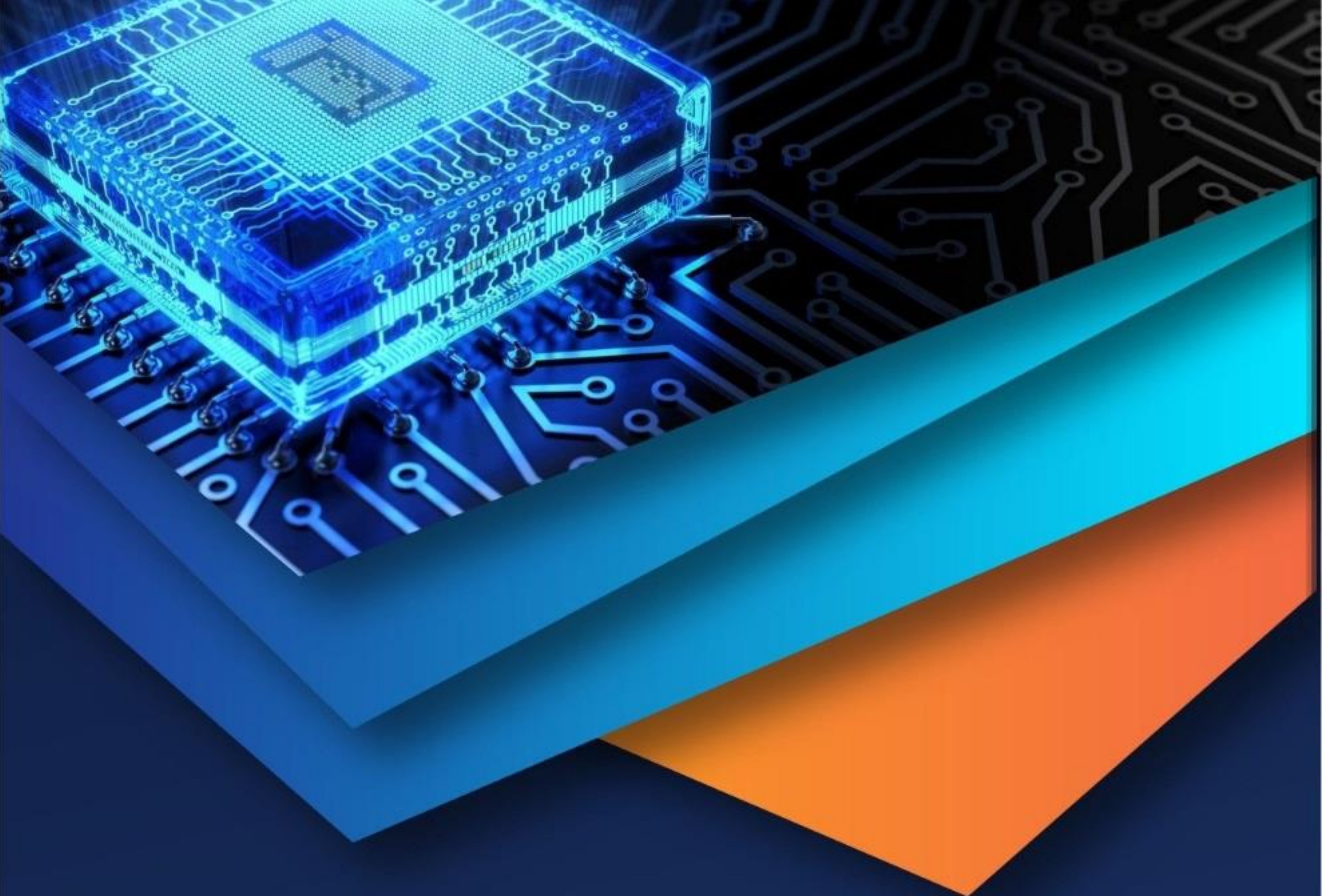

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