MAGMA

The MAGMA Approach to Effective Heat Treatment: Building Optimal Heat Transfer Curves

Think ahead to your target

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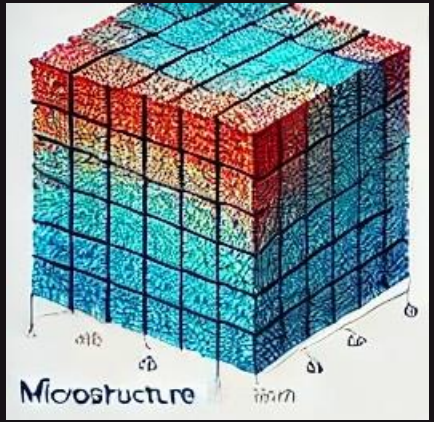
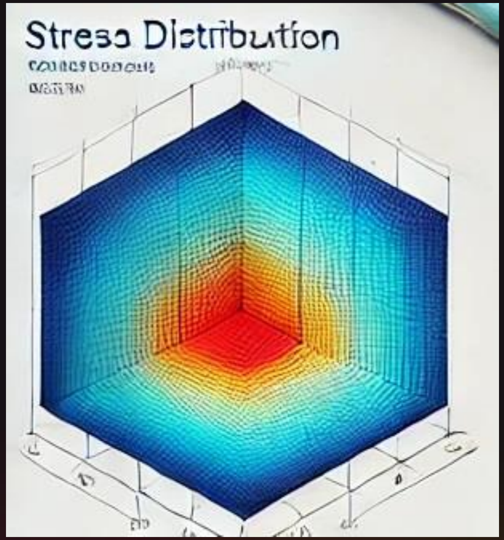
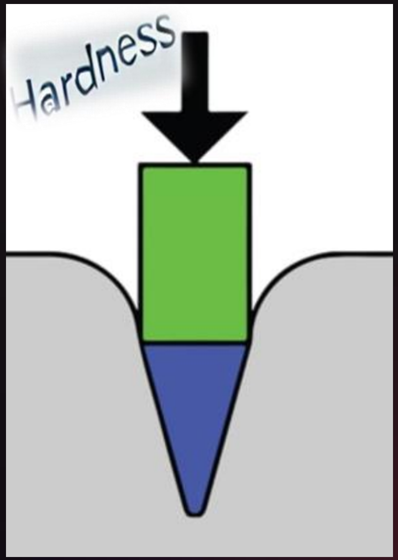
OBJECTIVES

Current Situation –

- Not able to determine influence of HTC on overall casting quality.
- Microstructure, Hardness, Stresses etc. are not predicted as HTC curves varying from shop floor data



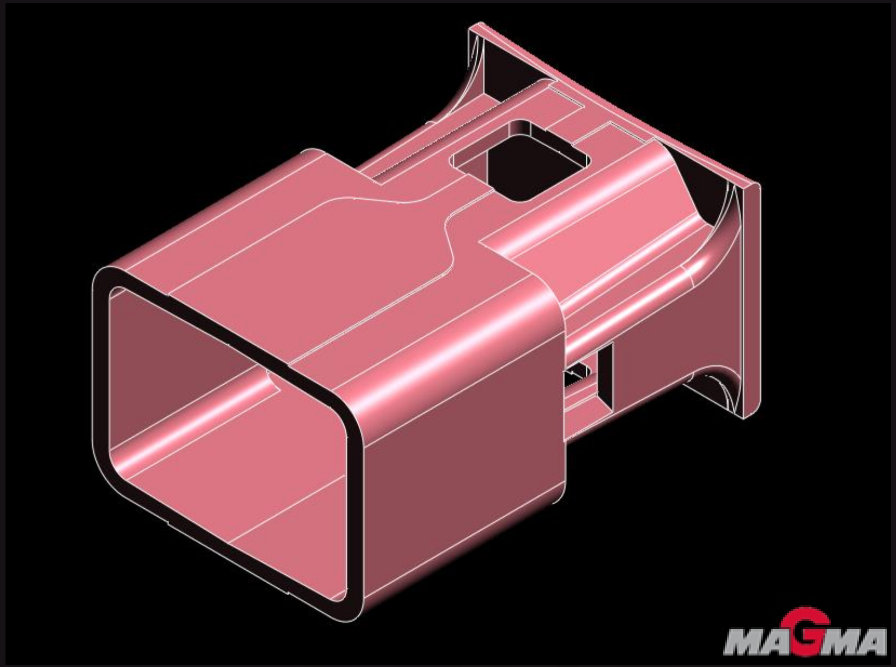




Analysis of the Initial State

Which Issue Needs to Be Solved?

- Suppose, There is deviation in Hardness and stresses
- Hardness & Stresses dependents on
  - What should be the Quench Medium ?
  - What should the Cooling rate ?
  - What type of Microstructure do we require?



DEFINE YOUR VARIABLES

Which Options, Variables and Flexibility Do I Have?

Temperature related variables –
1. Furnace Temperature
2. Casting Temperature
3. Ambient Temperature

Material related variables –
1. Thermal Conductivity
2. Specific Heat Capacity
3. Emissivity

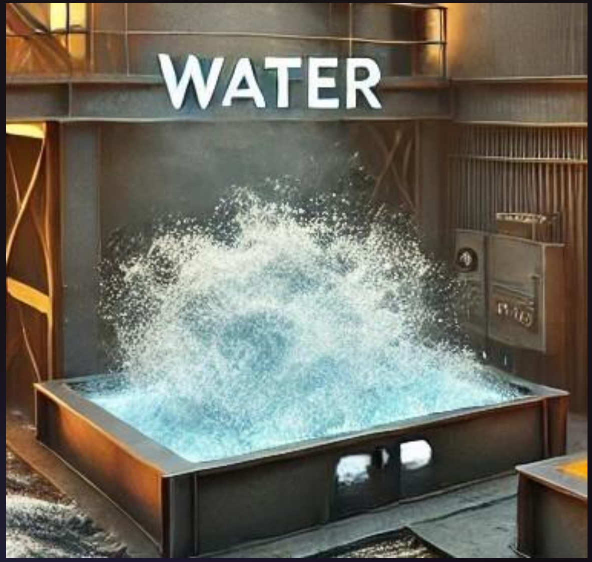
Time related variables –
1. Heating Time
2. Holding (Soaking) time
3. Cooling time

Environment related variables –
1. Cooling Medium (Air, Water, Oil)
2. Cooling medium temperature

Constraints–
1. Furnace & Casting Temperature assumed to be same throughout the furnace heating and cooling.
2. In case of forced cooling, HTC curves are created based on assumptions.
3. Water at 250°C is considered to be in liquid phase.

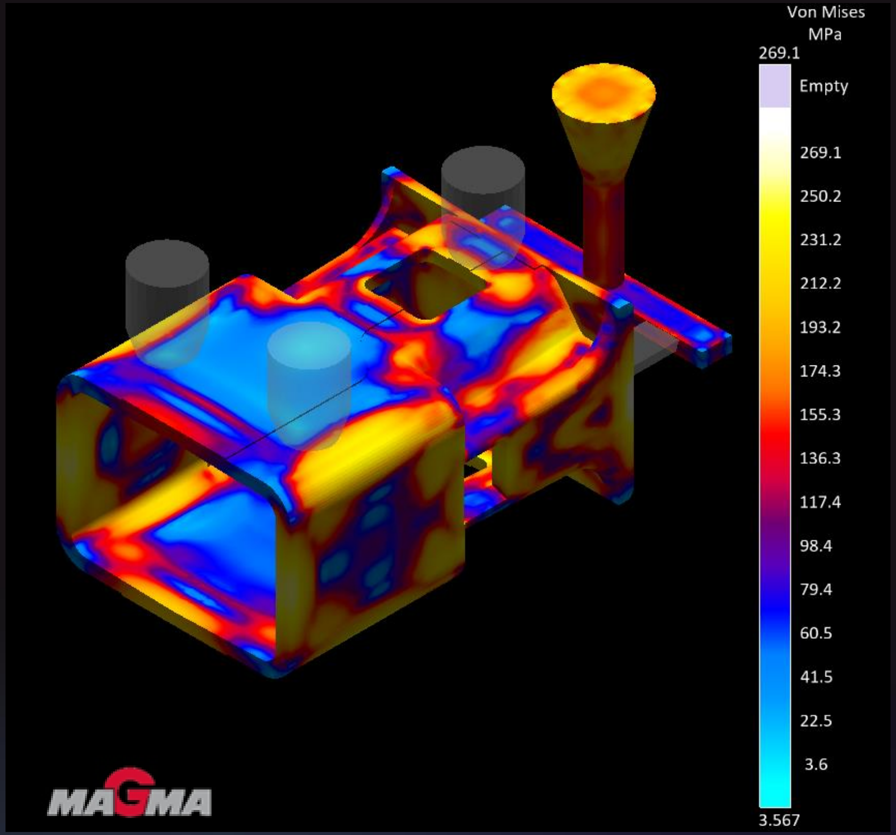
DEFINE YOUR VARIABLES

- We are going to consider only following in our case -
  - Environment related variables –
  - 1. Cooling Medium (Air, Water, Oil)
  - 2. Cooling medium temperature & HTC Cooling Curves



SPECIFIY YOUR CRITERIA

Which Quality Criteria Can Be Combined and Assessed?



Residual Stress Formation–

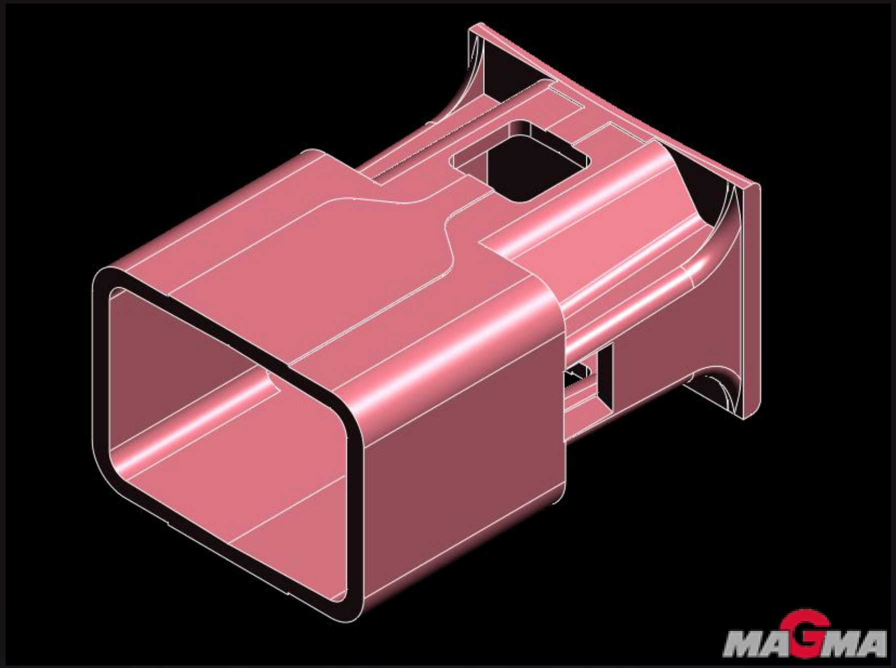
Location - Predominantly around mold-metal contact points and section transitions.
Description - Monitor areas prone to stress build-up to predict warping, cracking, or other defects due to thermal contraction

Objectives/Quality Criteria:

Stresses in probable crack areas

KEEP THE TASK EFFICIENT

Structure and Simplify the Complexity of Your Task!

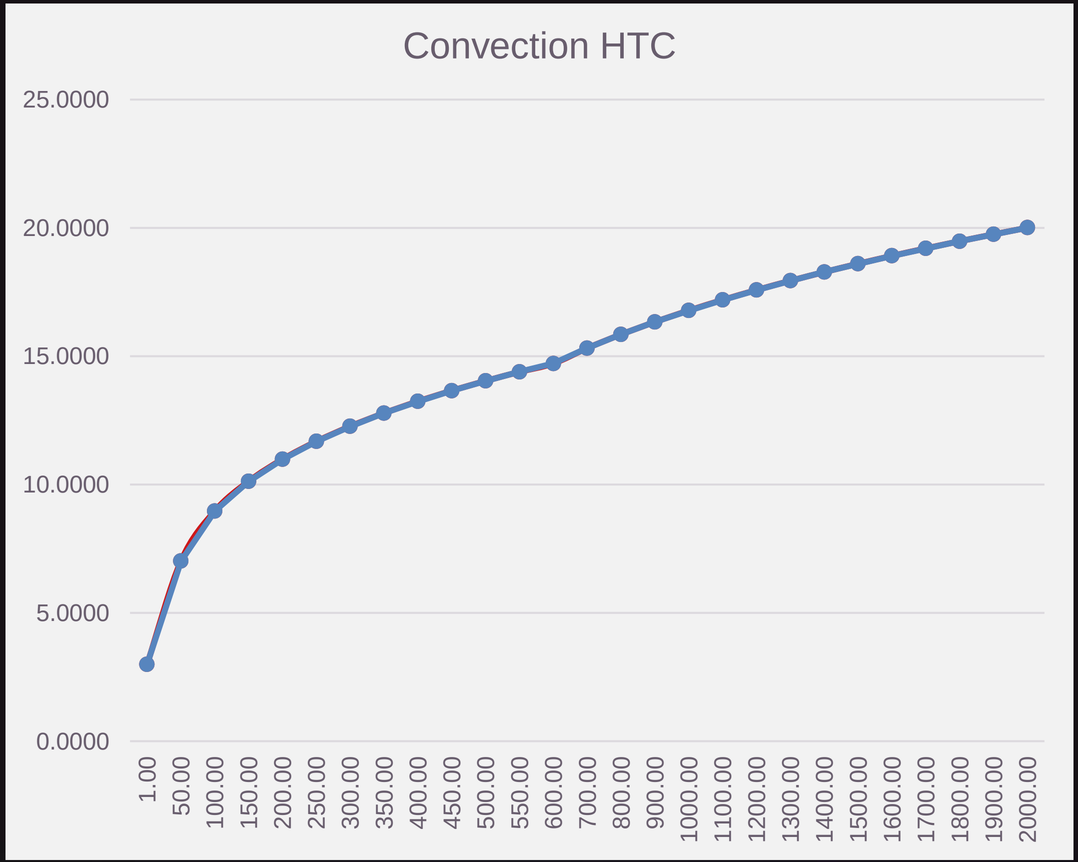


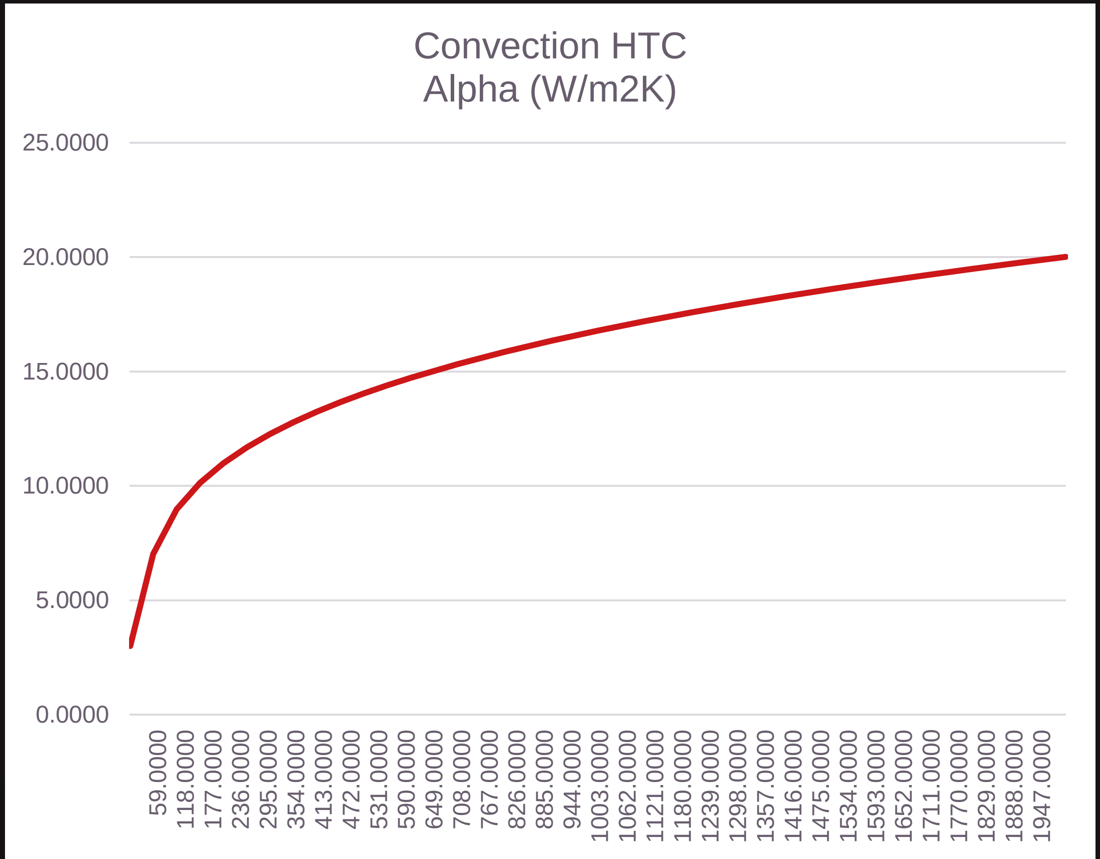
First task:
- Create your own HTC Curves using existing data
- Convert discrete values to smooth graphs
- Create HT cycles & separate heating curves e.g. Hardening, Tempering etc. as input to MagmaSoft

Second task:
- Prepare number of curves for cooling mediums
- Use optimization tool to simulate combination of temperature history and boundary conditions

Third task:
- Analyze effect of different boundary conditions on stresses and material properties

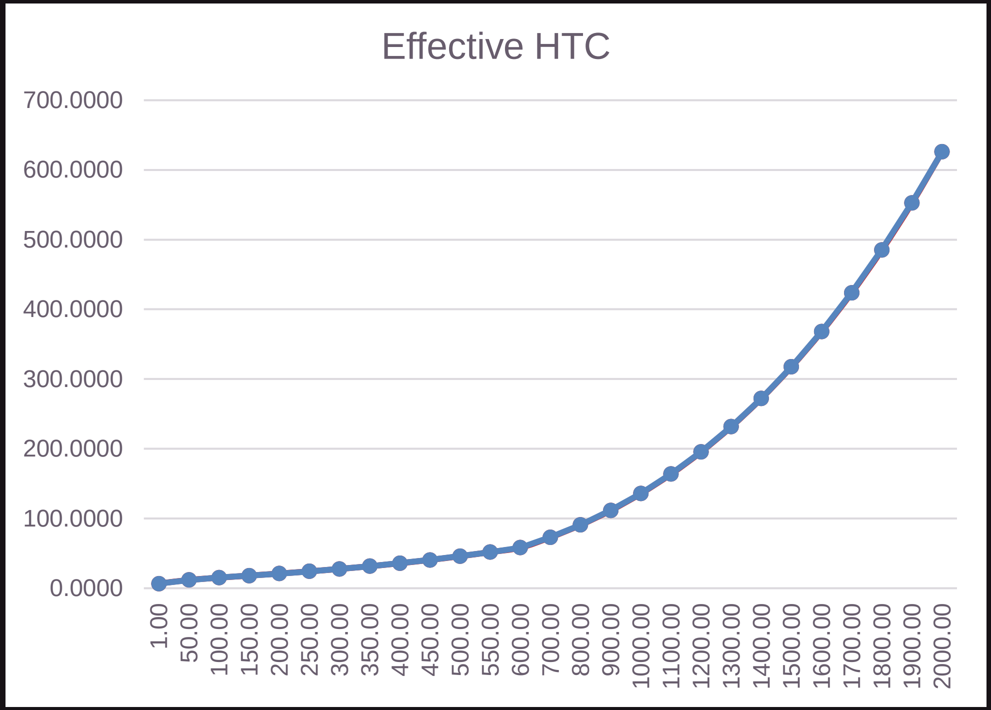
Create your own HTC Curves using existing data

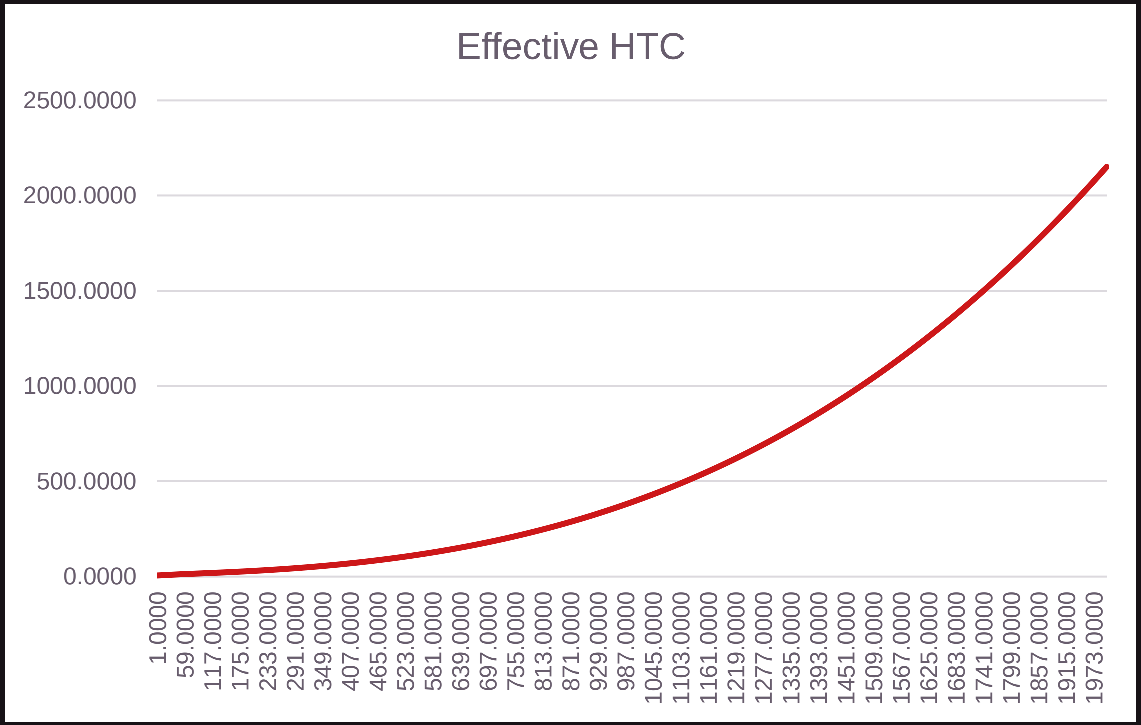




- Existing data

Create your own HTC Curves using existing data





Existing data

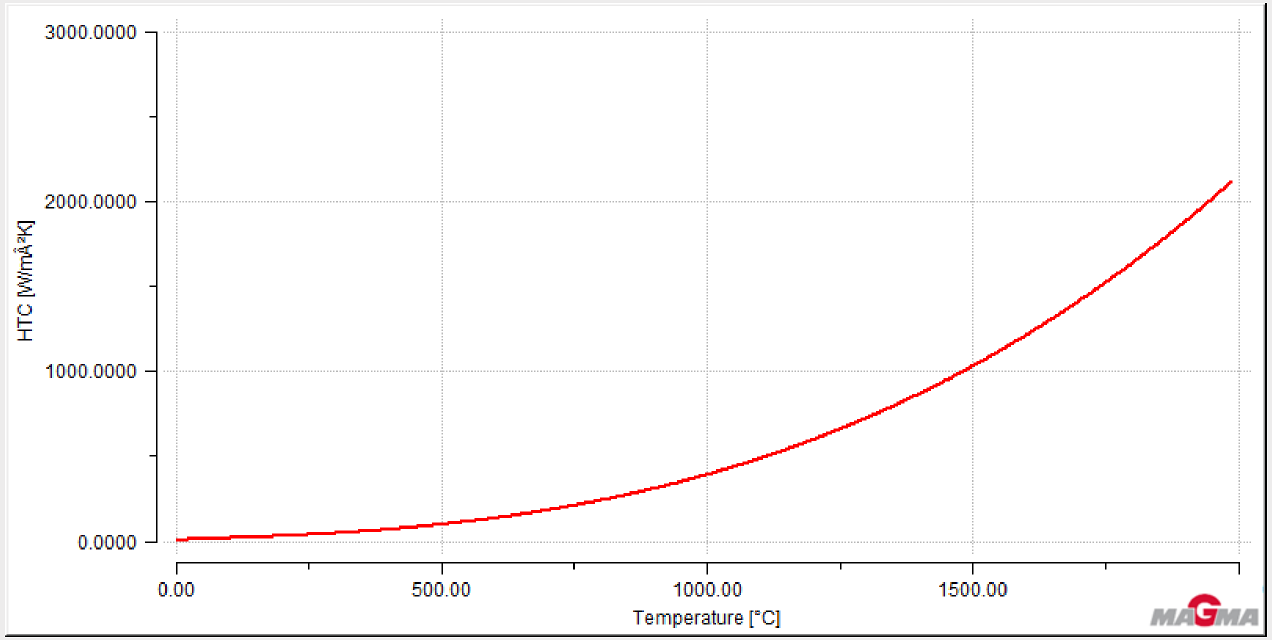
Create your own HTC Curves using existing data

Furnace Radiation & Convection

Boundary: Furnace_heated_and_Cooled

HTC as function of Temperature

Temperature [°C]	HTC [W/m²K]
1.00	6.7385
2.00	6.8616
3.00	6.9850
4.00	7.1088
5.00	7.2328
6.00	7.3571
7.00	7.4817
8.00	7.6067
9.00	7.7319
10.00	7.8575
11.00	7.9833
12.00	8.1095
13.00	8.2360
14.00	8.3627
15.00	8.4898
16.00	8.6173
17.00	8.7450
18.00	8.8730
19.00	9.0014
20.00	9.1301
21.00	9.2591
22.00	9.3884
23.00	9.5180
24.00	9.6480



This is the htc curve for condition while Workpiece is inside furnace either Heated or Cooled.

Effective HTC curve for Radiation and Convection Combined effect

HTC as function of Temperature

Temperature [°C]	HTC [W/m²K]
1978.00	2089.8408
1979.00	2092.6031
1980.00	2095.3677
1981.00	2098.1349
1982.00	2100.9045
1983.00	2103.6765
1984.00	2106.4510
1985.00	2109.2280
1986.00	2112.0074
1987.00	2114.7893
1988.00	2117.5737
1989.00	2120.3605
1990.00	2123.1497
1991.00	2125.9415
1992.00	2128.7357
1993.00	2131.5323
1994.00	2134.3315
1995.00	2137.1331
1996.00	2139.9371
1997.00	2142.7437
1998.00	2145.5527
1999.00	2148.3642
2000.00	2151.1781

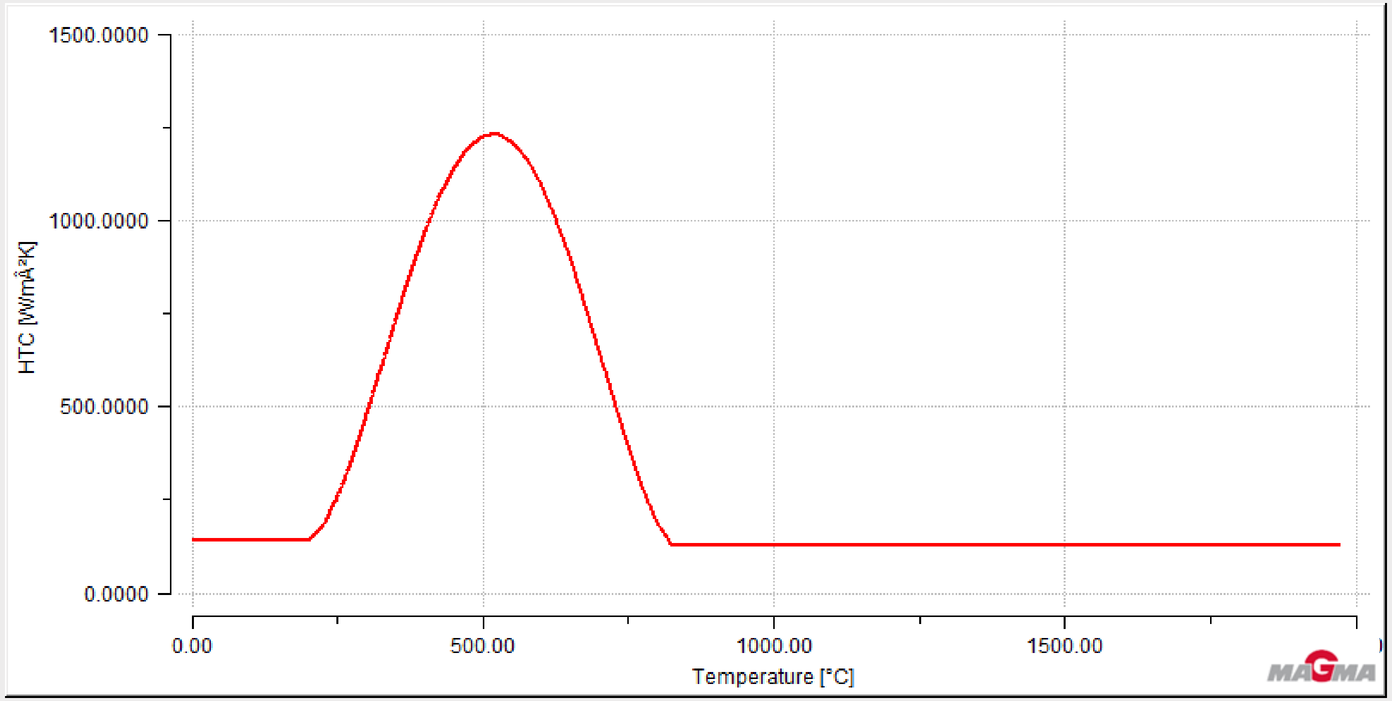
Create your own HTC Curves using existing data

Quenched Radiation & Convection

Boundary: Oil_Quenched

HTC as function of Temperature

Temperature [°C]	HTC [W/m²K]
1.00	141.0250
2.00	141.0250
3.00	141.0250
4.00	141.0250
5.00	141.0250
6.00	141.0250
7.00	141.0250
8.00	141.0250
9.00	141.0250
10.00	141.0250
11.00	141.0250
12.00	141.0250
13.00	141.0250
14.00	141.0250
15.00	141.0250
16.00	141.0250
17.00	141.0250
18.00	141.0250
19.00	141.0250
20.00	141.0250
21.00	141.0250
22.00	141.0250
23.00	141.0250
24.00	141.0250



Effective HTC curve for Radiation and Convection Combined effect

Temperature [°C]	HTC [W/m²K]
1978.00	125.6170
1979.00	125.6170
1980.00	125.6170
1981.00	125.6170
1982.00	125.6170
1983.00	125.6170
1984.00	125.6170
1985.00	125.6170
1986.00	125.6170
1987.00	125.6170
1988.00	125.6170
1989.00	125.6170
1990.00	125.6170
1991.00	125.6170
1992.00	125.6170
1993.00	125.6170
1994.00	125.6170
1995.00	125.6170
1996.00	125.6170
1997.00	125.6170
1998.00	125.6170
1999.00	125.6170
2000.00	125.6170

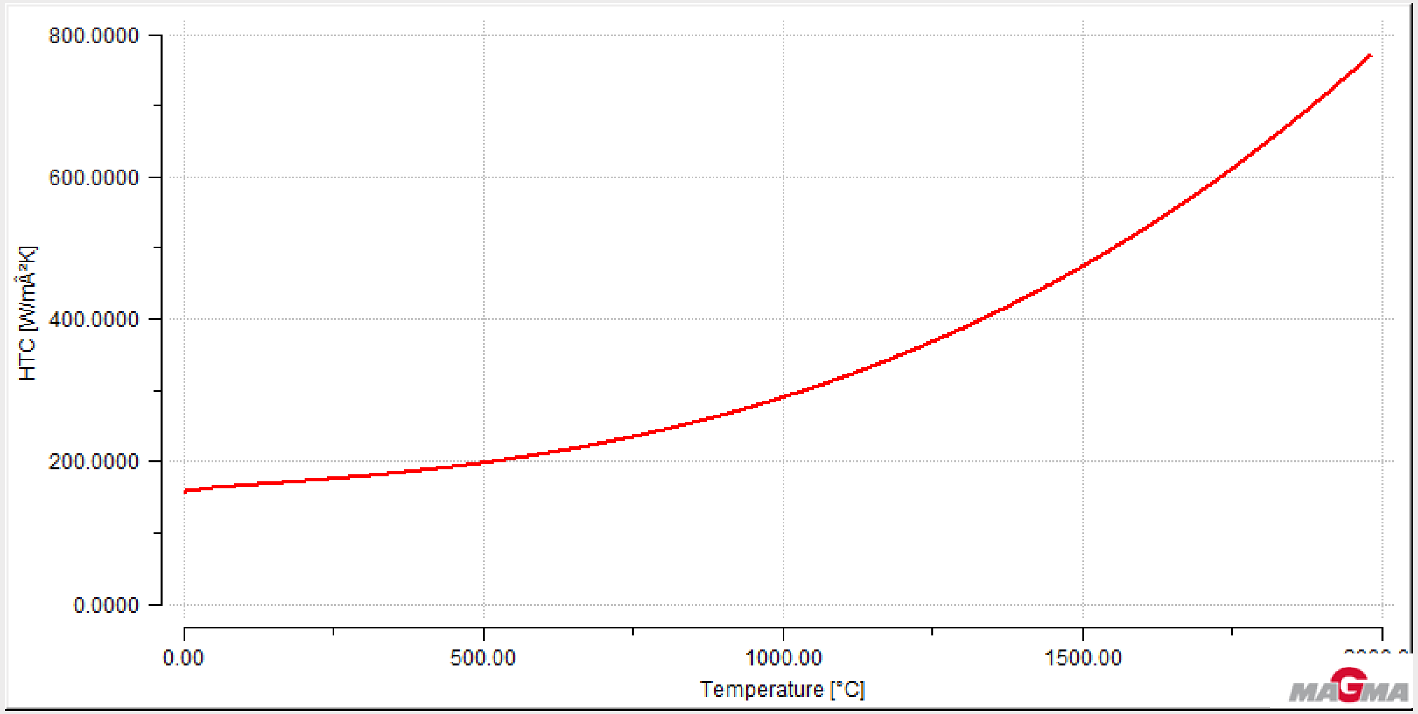
This is the htc curve for condition while Workpiece is Oil quenched.

Create your own HTC Curves using existing data
Forced Air Cooling Radiation & Convection

Boundary: Forced_Air_Cooled

HTC as function of Temperature

Temperature [°C]	HTC [W/m²K]
1.00	157.3746
2.00	157.4787
3.00	157.5828
4.00	157.6871
5.00	157.7914
6.00	157.8959
7.00	158.0005
8.00	158.1051
9.00	158.2099
10.00	158.3148
11.00	158.4198
12.00	158.5248
13.00	158.6300
14.00	158.7353
15.00	158.8407
16.00	158.9462
17.00	159.0518
18.00	159.1576
19.00	159.2634
20.00	159.3693
21.00	159.4754
22.00	159.5815
23.00	159.6878
24.00	159.7941



Effective HTC curve for Radiation and Convection Combined effect

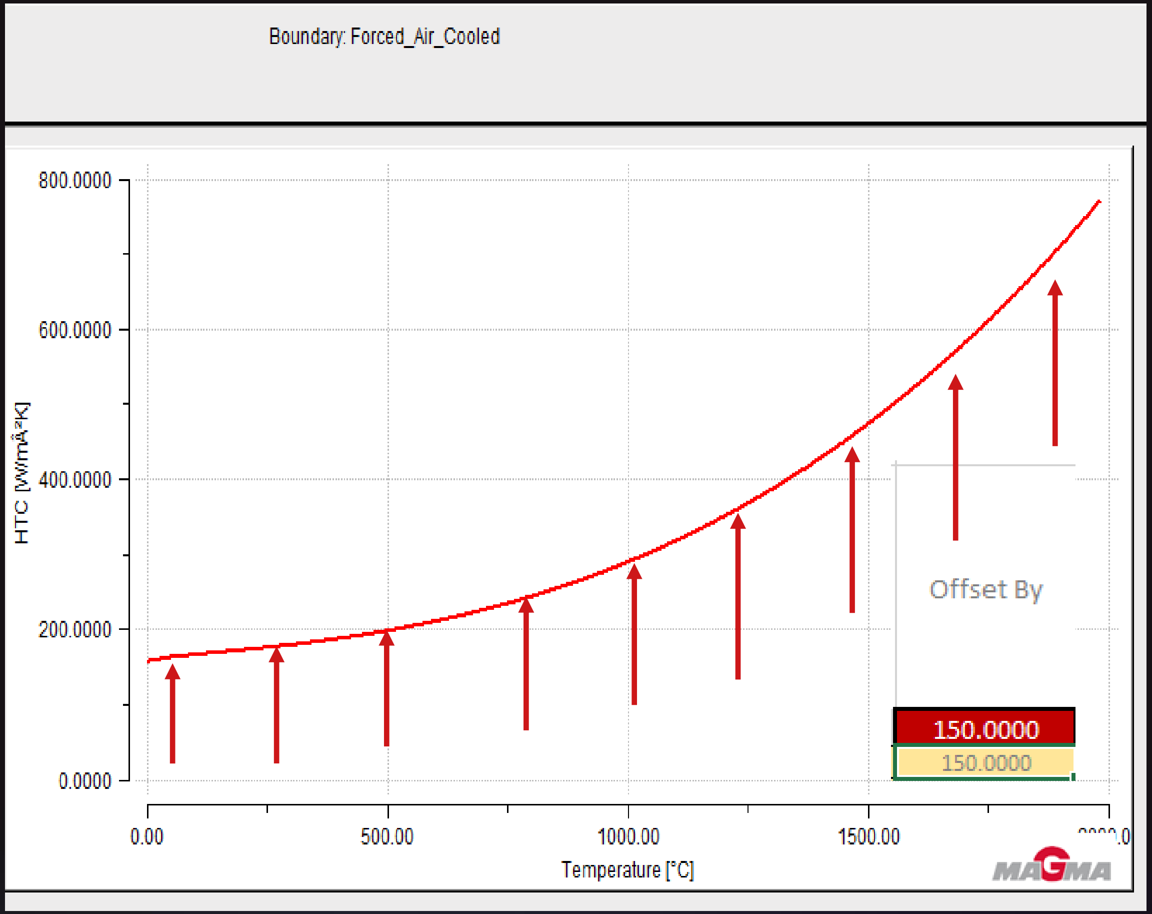
HTC as function of Temperature

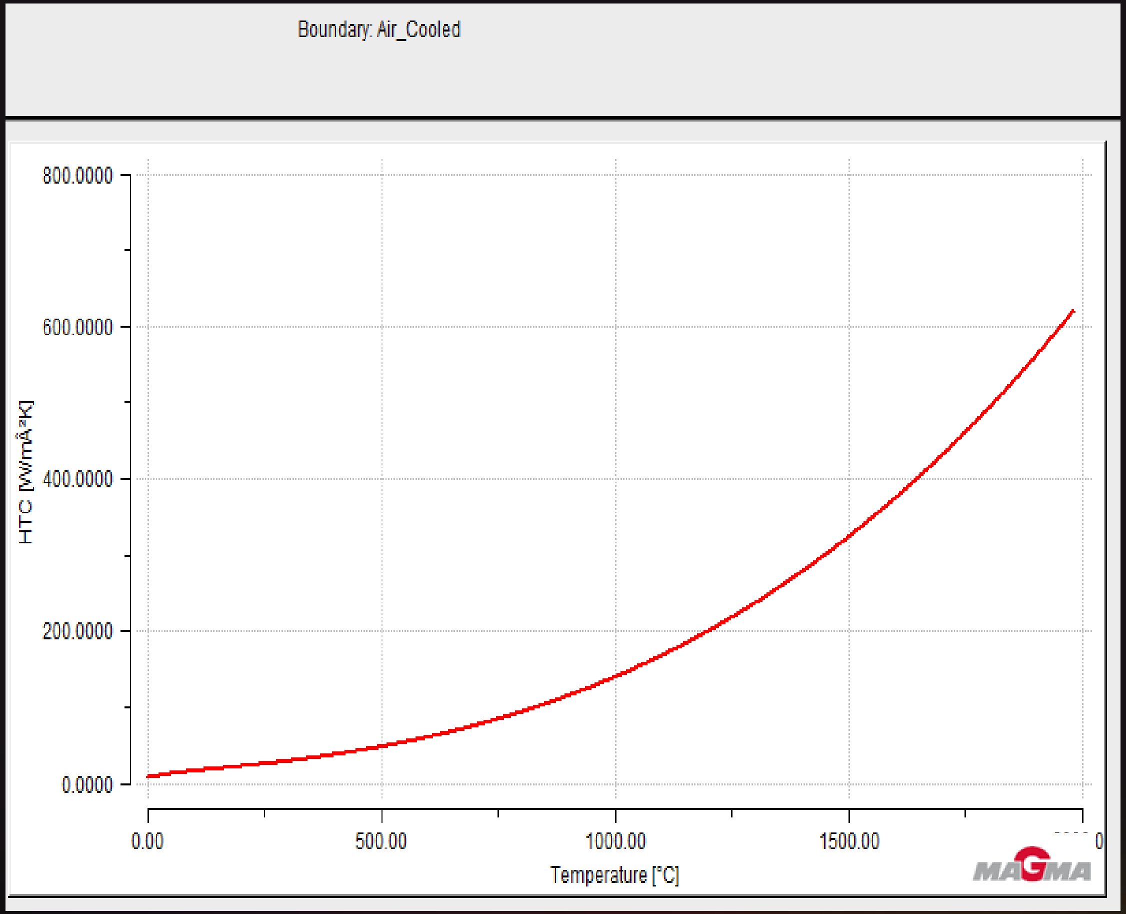
Temperature [°C]	HTC [W/m²K]
1978.00	767.7595
1979.00	768.5180
1980.00	769.2773
1981.00	770.0371
1982.00	770.7976
1983.00	771.5588
1984.00	772.3206
1985.00	773.0830
1986.00	773.8461
1987.00	774.6098
1988.00	775.3742
1989.00	776.1392
1990.00	776.9048
1991.00	777.6711
1992.00	778.4380
1993.00	779.2056
1994.00	779.9738
1995.00	780.7427
1996.00	781.5122
1997.00	782.2823
1998.00	783.0531
1999.00	783.8246
2000.00	784.5967

This is the htc curve for condition while Workpiece is Air Cooled using Fans and accessories.

Short Note-

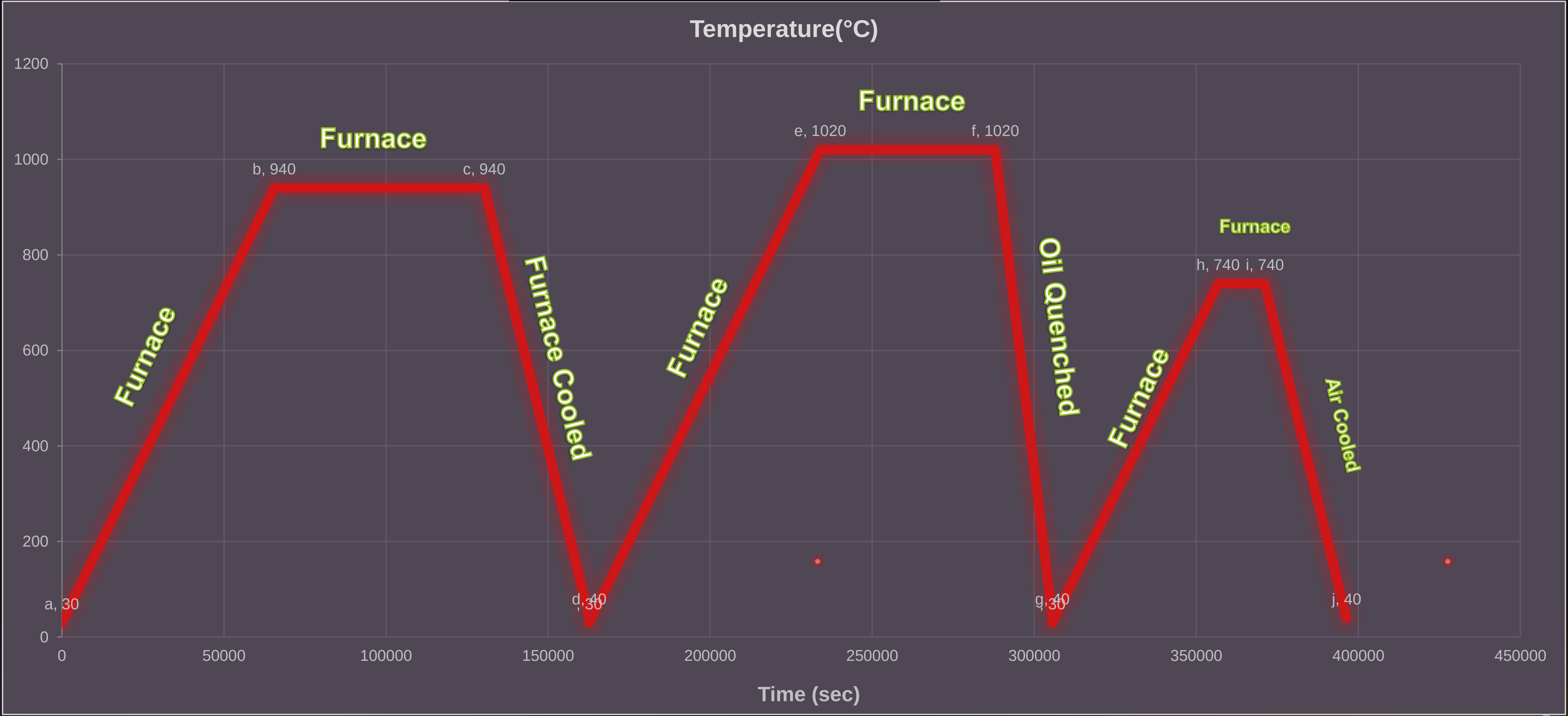
Difference between Forced Air Cooled & Air Cooled



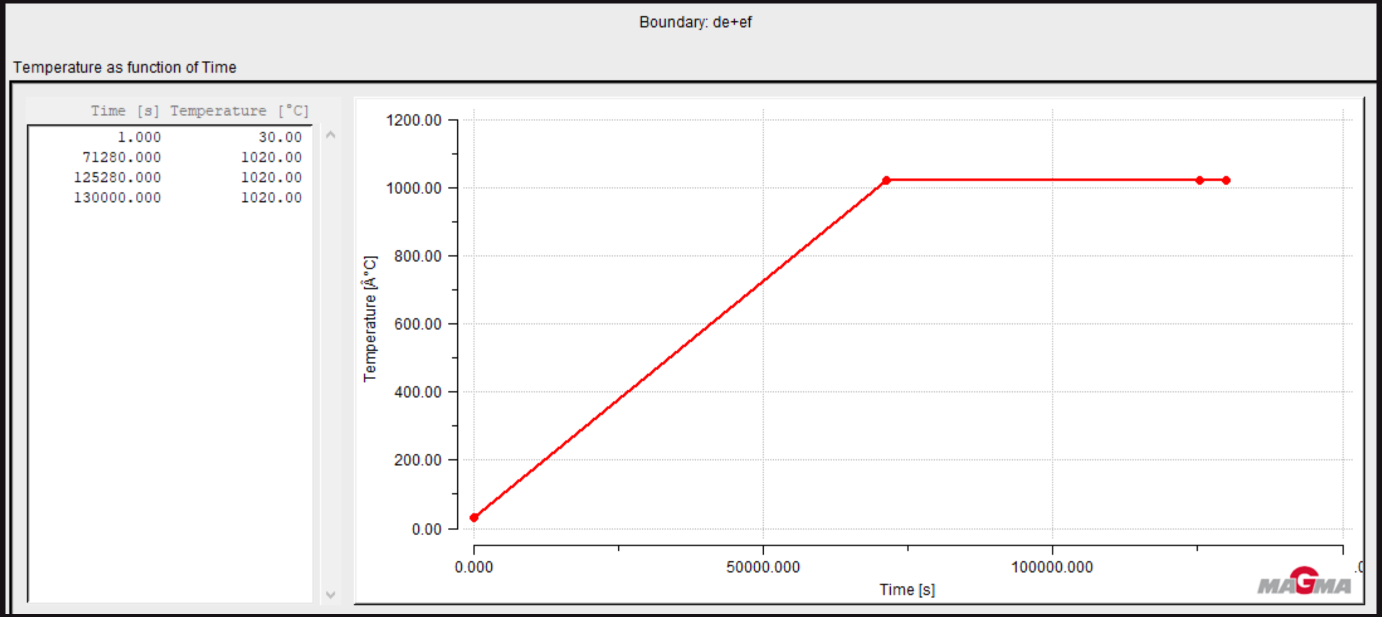


200 units step added to value to compromise the increased convection heat transfer effect.

Heat Treatment Cycle



Hardening

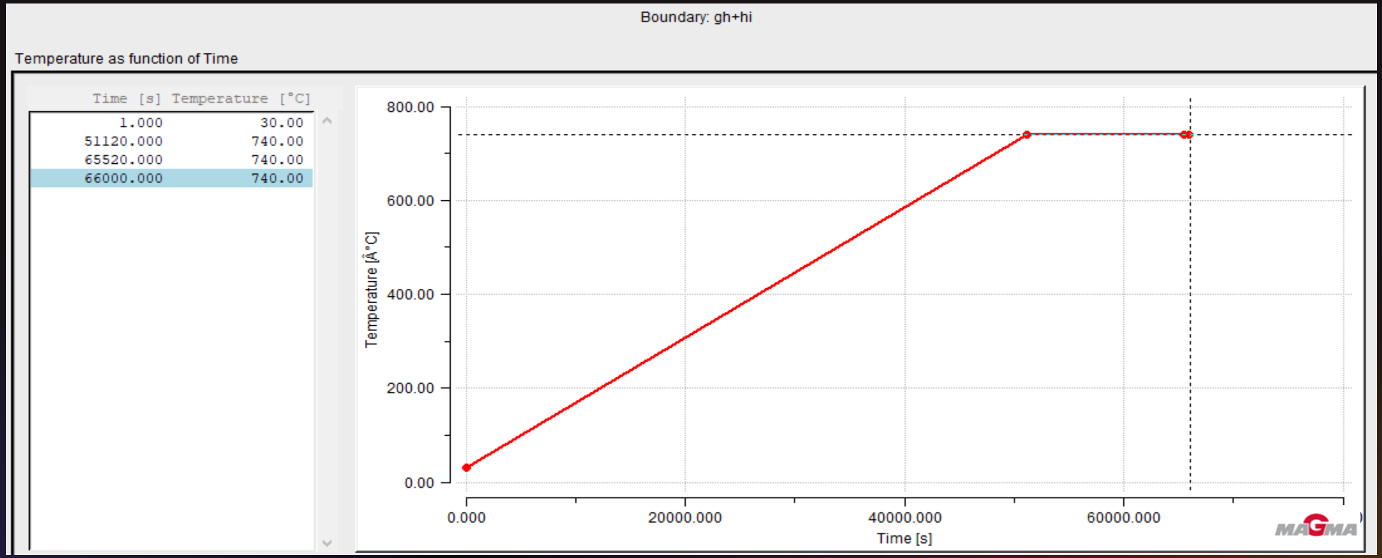


de+ef

Hardening Heating Curve

From 30°C to 1020°C

Tempering



gh+hi

Tempering Heating Curve

From 30°C to 740°C

Provide boundary conditions for Radiation & Convection

Oil Quench

Steps in Heat Treatment Process

Step	Type	Temperature History	Stop Condition
001	Austenitization	User/de+ef	after 130320.0 s
002	Quenching	MAGMA/Steel_Quench_25C	after 162720.0 s
003	Tempering	User/gh+hi	after 125280.0 s
004	Cooling	MAGMA/Steel_Air_cooling	as soon as max. temp. in Casting ID 1 falls below 40.0 °C

Boundary Definition

Material 1	Mat ID	Material 2	Mat ID	Database/Filename	Type
Cast Alloy		Cast Alloy		User/Oil_Quenched	Heat Transfer Coefficient
Cast Alloy		Sand Mold		User/Oil_Quenched	Heat Transfer Coefficient
Cast Alloy		Sleeve		User/Oil_Quenched	Heat Transfer Coefficient

Force Air Cooled

Steps in Heat Treatment Process

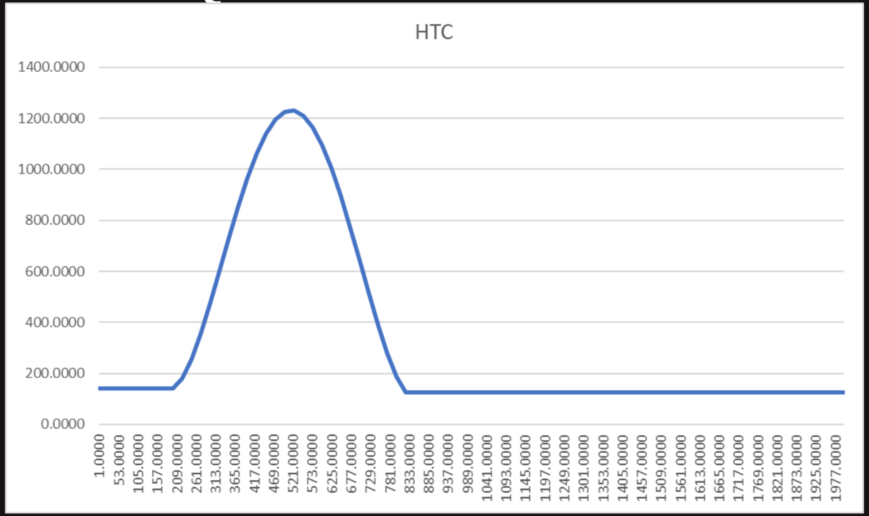
Step	Type	Temperature History	Stop Condition
001	Austenitization	User/de+ef	after 130320.0 s
002	Quenching	MAGMA/Steel_Quench_25C	after 162720.0 s
003	Tempering	User/gh+hi	after 125280.0 s
004	Cooling	MAGMA/Steel_Air_cooling	as soon as max. temp. in Casting ID 1 falls below 40.0 °C

Boundary Definition

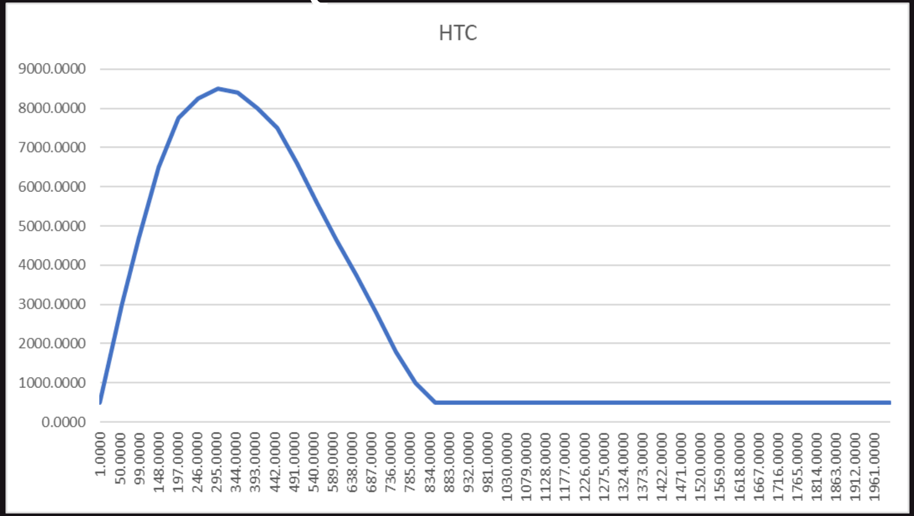
Material 1	Mat ID	Material 2	Mat ID	Database/Filename	Type
Cast Alloy		Cast Alloy		User/Forced_Air_Cooled	Heat Transfer Coefficient
Cast Alloy		Sand Mold		User/Forced_Air_Cooled	Heat Transfer Coefficient
Cast Alloy		Sleeve		User/Forced_Air_Cooled	Heat Transfer Coefficient

Multiple boundary conditions HTC Curves for Optimization

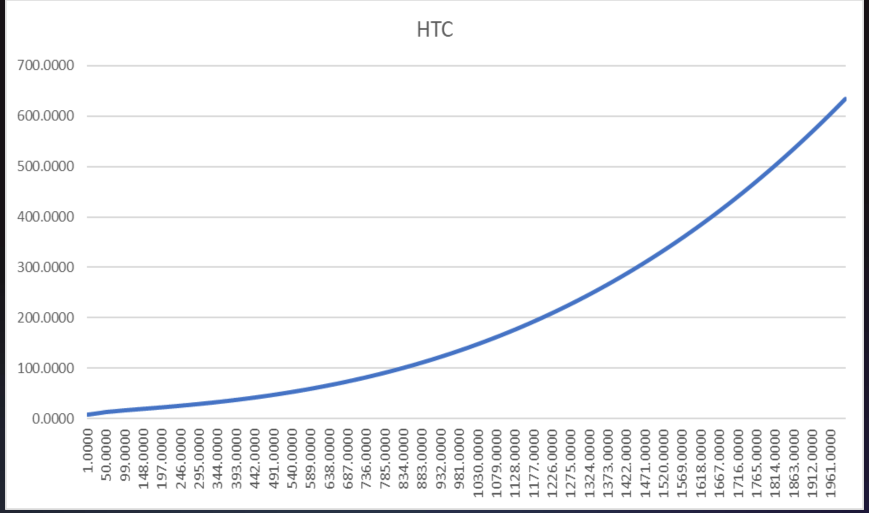
Oil Quench



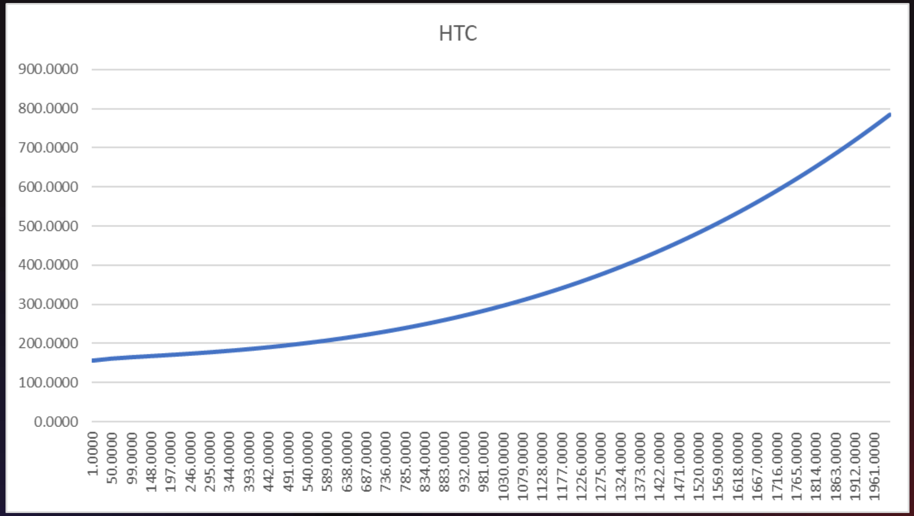
Water Quench



Air Cooled



Force Air Cooled



Excel sheets can be used to create HTC using following data -

Radiation Emissivity Factor (Epsilon)	Environment Temperature (°C)	Workpiece Temprature (°C)	Convection HTC Alpha (W/m^2K)	Offset By
0	30			0.0000
0	30.0	1.00	141.0250	0.0000
	30.0	200.00	141.0250	
	30.0	225.00	180.2700	
	30.0	250.00	255.0000	
	30.0	275.00	357.0000	
	30.0	300.00	475.0000	
	30.0	325.00	602.0000	
	30.0	350.00	730.0000	
	30.0	375.00	853.0000	
	30.0	400.00	966.0000	
	30.0	425.00	1062.0000	
	30.0	450.00	1140.0000	
	30.0	475.00	1195.0000	
	30.0	500.00	1225.0000	
	30.0	525.00	1231.0000	
	30.0	550.00	1210.0000	
	30.0	575.00	1165.0000	
	30.0	600.00	1096.0000	
	30.0	625.00	1007.0000	
	30.0	650.00	899.0000	
	30.0	700.00	650.0000	
	30.0	725.00	519.0000	
	30.0	750.00	393.0000	
	30.0	775.00	279.0000	
	30.0	800.00	187.1410	
	30.0	825.00	125.6170	
	30.0	2000.00	125.6170	

Workpiece Temprature (°C)	Ultimate HTC Considering Equal Temp of Workpiece & Furnace at an Instant
201.0000	142.5948
202.0000	144.1646
203.0000	145.7344
204.0000	147.3042
205.0000	148.8740
206.0000	150.4438
207.0000	152.0136
208.0000	153.5834
209.0000	155.1532
210.0000	156.7230
211.0000	158.2928
212.0000	159.8626
213.0000	161.4324
214.0000	163.0022
215.0000	164.5720
216.0000	166.1418
217.0000	167.7116
218.0000	169.2814
219.0000	170.8512
220.0000	172.4210
221.0000	173.9908
222.0000	175.5606
223.0000	177.1304
224.0000	178.7002
225.0000	180.2700
226.0000	183.2592
227.0000	186.2484
228.0000	189.2376
229.0000	192.2268

600.0000	1096.0000
601.0000	1092.4400
602.0000	1088.8800
603.0000	1085.3200
604.0000	1081.7600
605.0000	1078.2000
606.0000	1074.6400
607.0000	1071.0800
608.0000	1067.5200
609.0000	1063.9600
610.0000	1060.4000
611.0000	1056.8400
612.0000	1053.2800
613.0000	1049.7200
614.0000	1046.1600
615.0000	1042.6000
616.0000	1039.0400

Notepad

Import .txt To Database

CHOOSE YOUR METHOD

- Which MAGMASOFT® Optimization Tools Are Most Appropriate and Effective to Reach Your Objective?

DoE (8 Designs)-

- Two different Quench Mediums (Oil & Water)
- Quench Medium at two different temperatures (25°C & 250°C)
- Two different air cooling conditions (Simply Cooling in open air & Forced air Cooling.

Comparisons -

- Max. Principal Stress
- Von-Mises stress
- Hardness, Microstructure etc.

DoE (8 Designs)

Design Variables

	Design Variable	Dataset List	Dependency
☑	002 Quenching - Temperature History	User/Steel_Quench_25C User/Steel_Quench_250C	<None>
☑	002 Quenching - Boundary Data - Boundary ID 1 / Casting ID 1	User/Oil_Quenched User/Water_Quench	<None>
☑	004 Cooling - Boundary Data - Boundary ID 1 / Casting ID 1	User/Air_Cooled User/Forced_Air_Cooled	<None>

Objectives

- Reduce Max. Principal Stress (Casting Process)
- Reduce Max. Principal Stress (Heat Treatment)
- Reduce Von Mises Stress (Casting Process)
- Reduce Von Mises Stress (Heat Treatment)

Start Sequence

Design ID	002 Quenching - Temperature History	002 Quenching - Boundary Data - Boundary ID 1 / Casting ID 1	004 Cooling - Boundary Data - Boundary ID 1 / Casting ID 1
1	User/Steel_Quench_25C	User/Oil_Quenched	User/Air_Cooled
2	User/Steel_Quench_250C	User/Oil_Quenched	User/Air_Cooled
3	User/Steel_Quench_25C	User/Water_Quench	User/Air_Cooled
4	User/Steel_Quench_250C	User/Water_Quench	User/Air_Cooled
5	User/Steel_Quench_25C	User/Oil_Quenched	User/Forced_Air_Cooled
6	User/Steel_Quench_250C	User/Oil_Quenched	User/Forced_Air_Cooled
7	User/Steel_Quench_25C	User/Water_Quench	User/Forced_Air_Cooled
8	User/Steel_Quench_250C	User/Water_Quench	User/Forced_Air_Cooled

Assessment of DoEs

Overview -

Rank	Design	Reduce Max. Principal Str...	Reduce Max. Principal Str...	Reduce Von Mises Stress ...	Reduce Von Mises Stress (...
Rank 1	Design 2	139.49	18.75	113.25	30.39
Rank 2	Design 6	139.49	18.8	113.25	30.92
Rank 5	Design 1	139.49	24.93	113.25	31.67
Rank 6	Design 5	139.49	24.93	113.25	32.19
Rank 4	Design 8	139.49	27.31	113.25	29.36
Rank 3	Design 4	139.49	27.39	113.25	28.86
Rank 8	Design 7	139.49	32.93	113.25	32.4
Rank 7	Design 3	139.49	32.98	113.25	31.88

Rank	Design	Reduce Max. Principal Str...	Reduce Max. Principal Str...	Reduce Von Mises Stress ...	Reduce Von Mises Stress (...
Rank 3	Design 4	139.49	27.39	113.25	28.86
Rank 4	Design 8	139.49	27.31	113.25	29.36
Rank 1	Design 2	139.49	18.75	113.25	30.39
Rank 2	Design 6	139.49	18.8	113.25	30.92
Rank 5	Design 1	139.49	24.93	113.25	31.67
Rank 7	Design 3	139.49	32.98	113.25	31.88
Rank 6	Design 5	139.49	24.93	113.25	32.19
Rank 8	Design 7	139.49	32.93	113.25	32.4

Finding –
Von-Mises is generally used to determine yield failure criteria

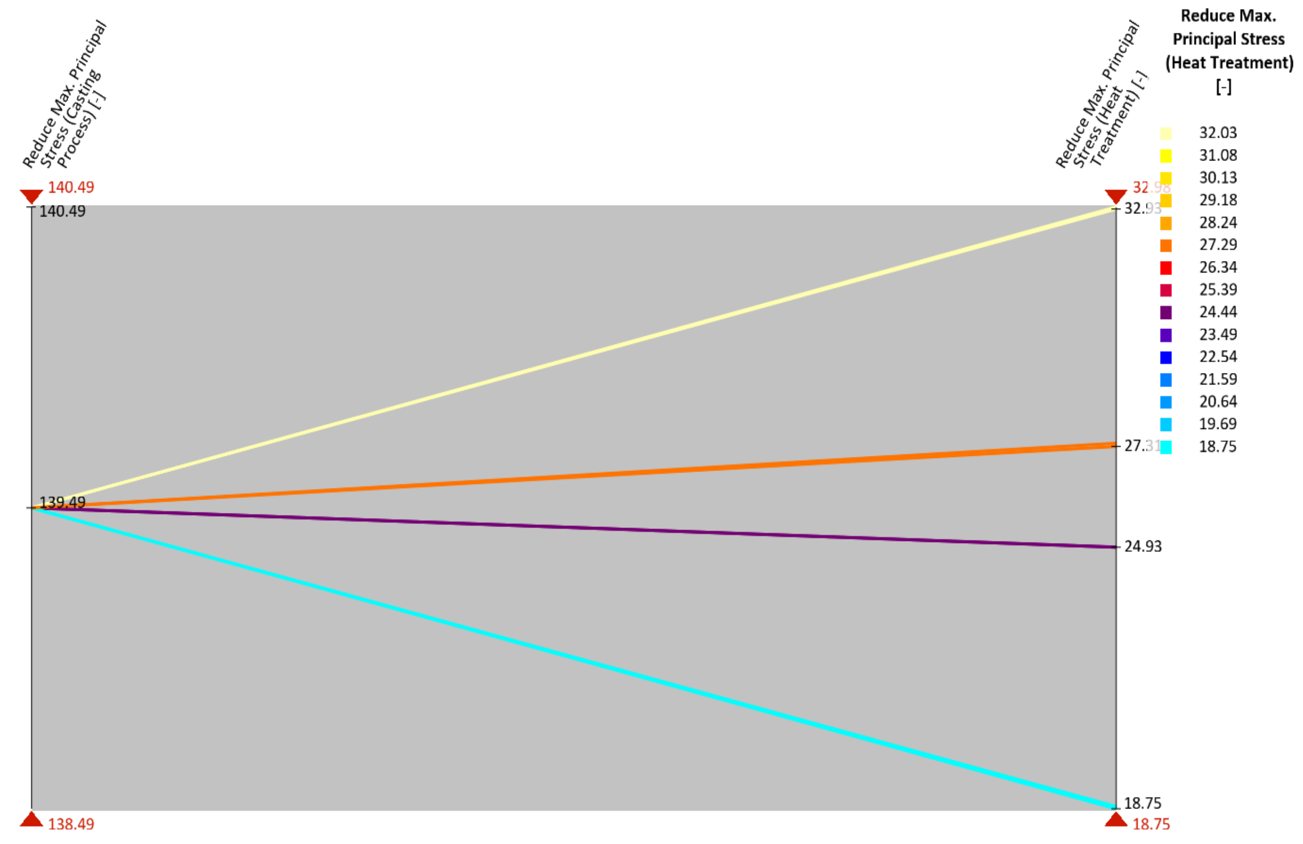
Max principal are more 'real' and directly measure stresses

Assessment of DoEs

Parallel Coordinates -

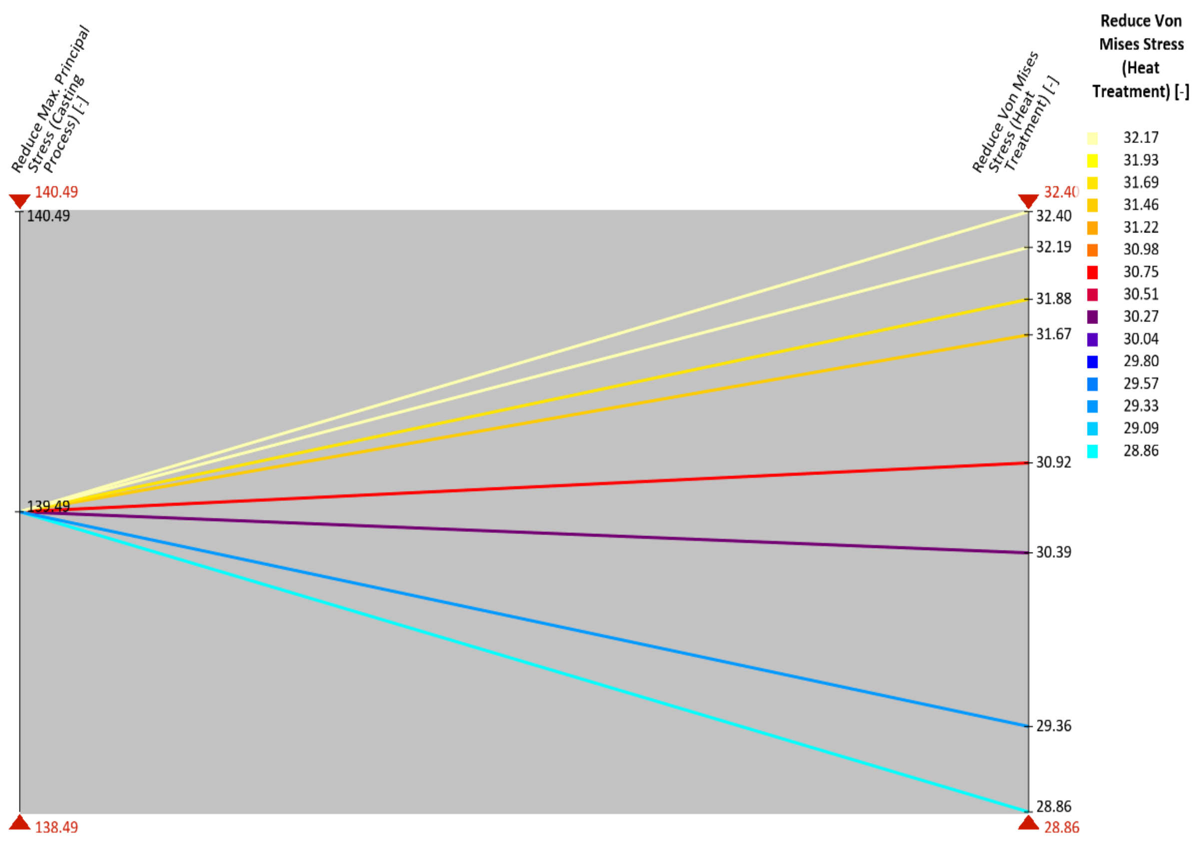
Reduced Max. Principal Stress (Casting Process)

Reduced Max. Principal Stress (Heat Treatment)

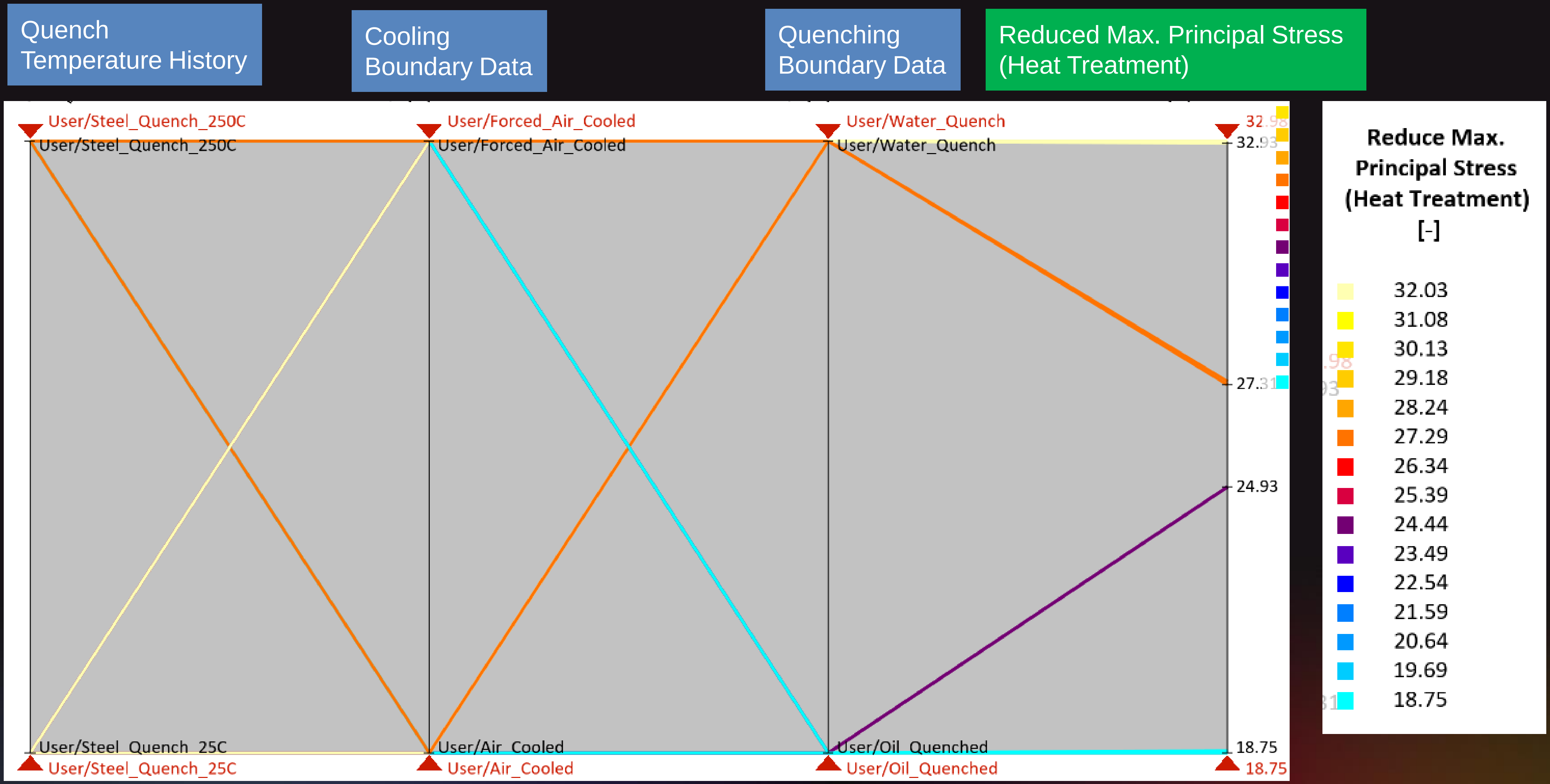


Reduced Von Mises Stress (Casting Process)

Reduced Von Mises Stress (Heat Treatment)



Assessment of DoEs



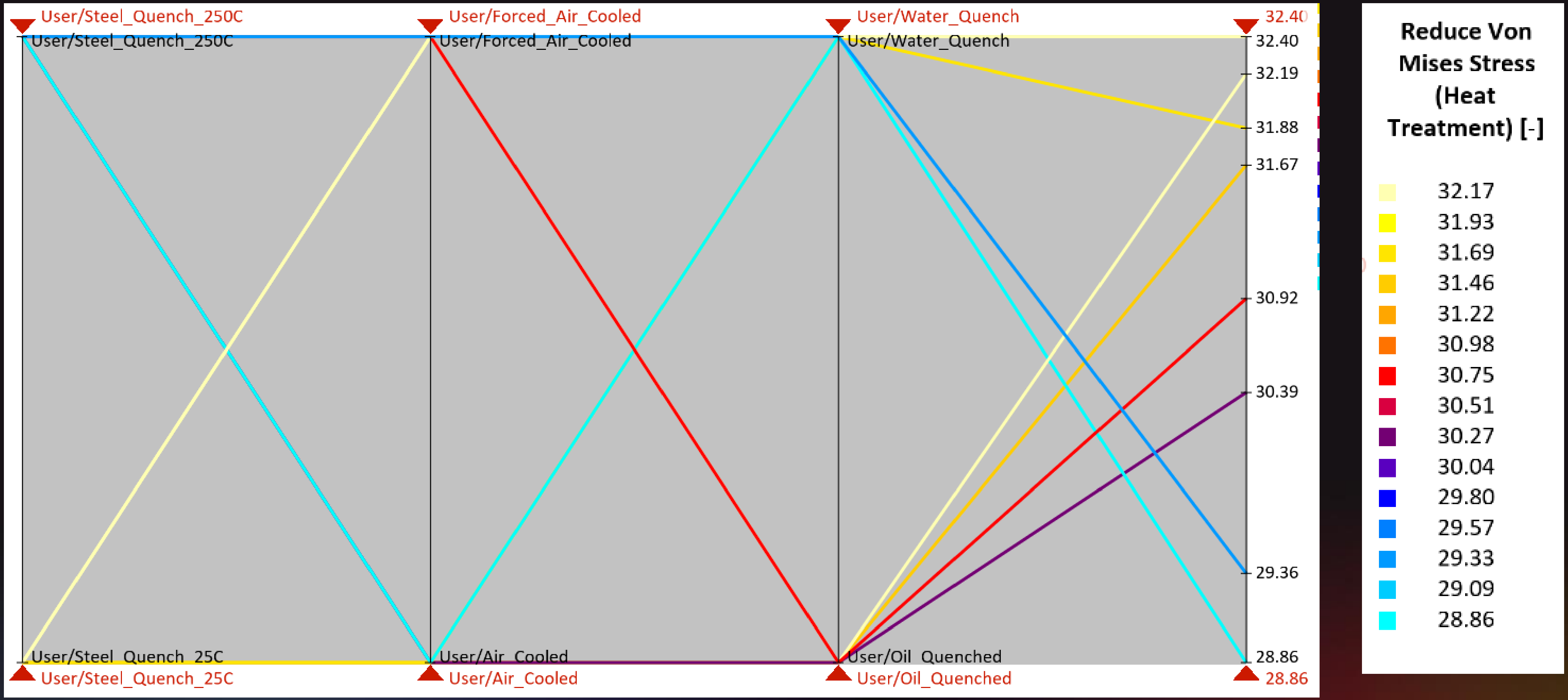
Assessment of DoEs

Quench Temperature History

Cooling Boundary Data

Quenching Boundary Data

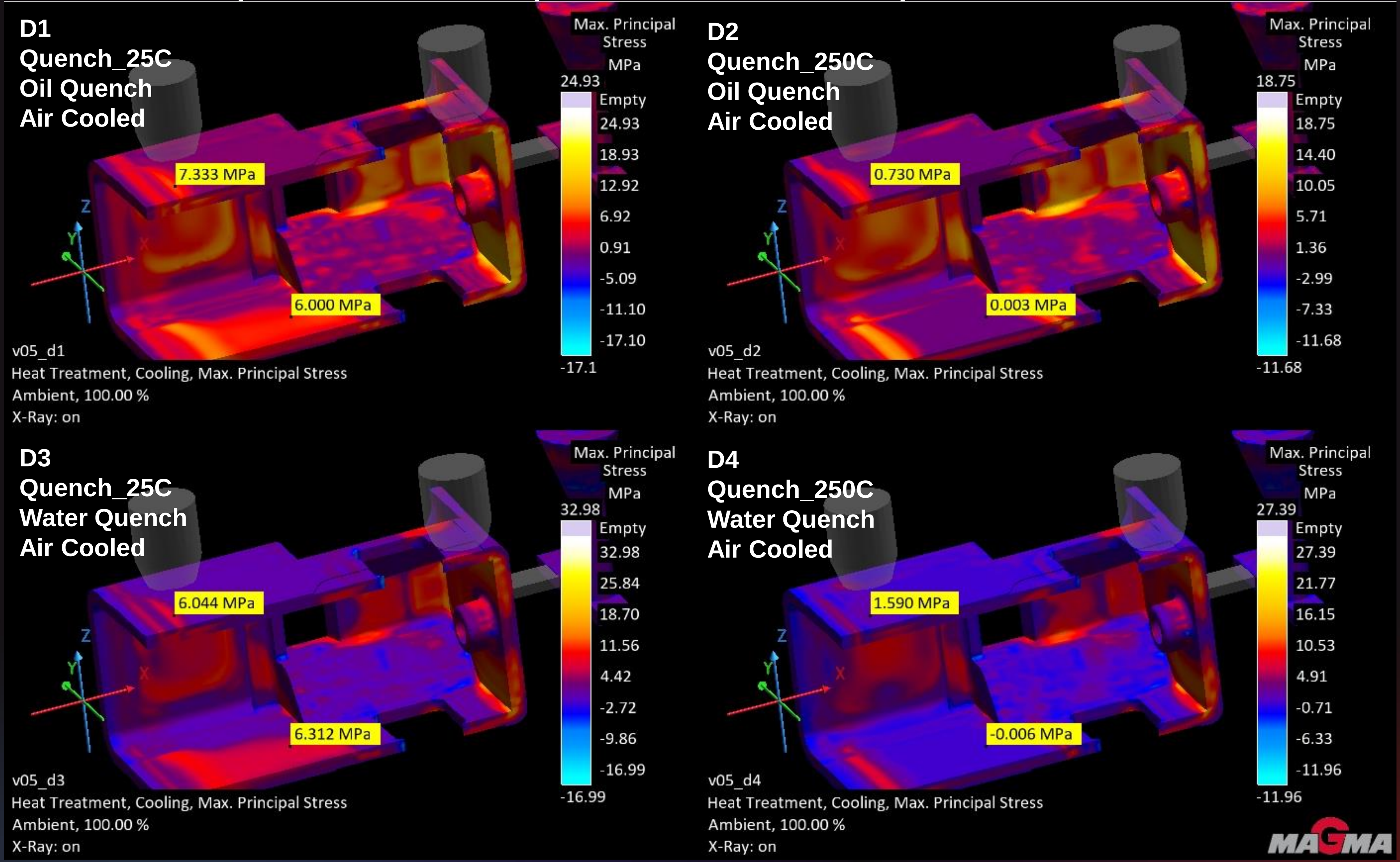
Reduced Von Mises Stress (Heat Treatment)



ACT & CHECK IMPROVEMENTS

Results Assessment

Max Principal Stresses (Heat Treatment)

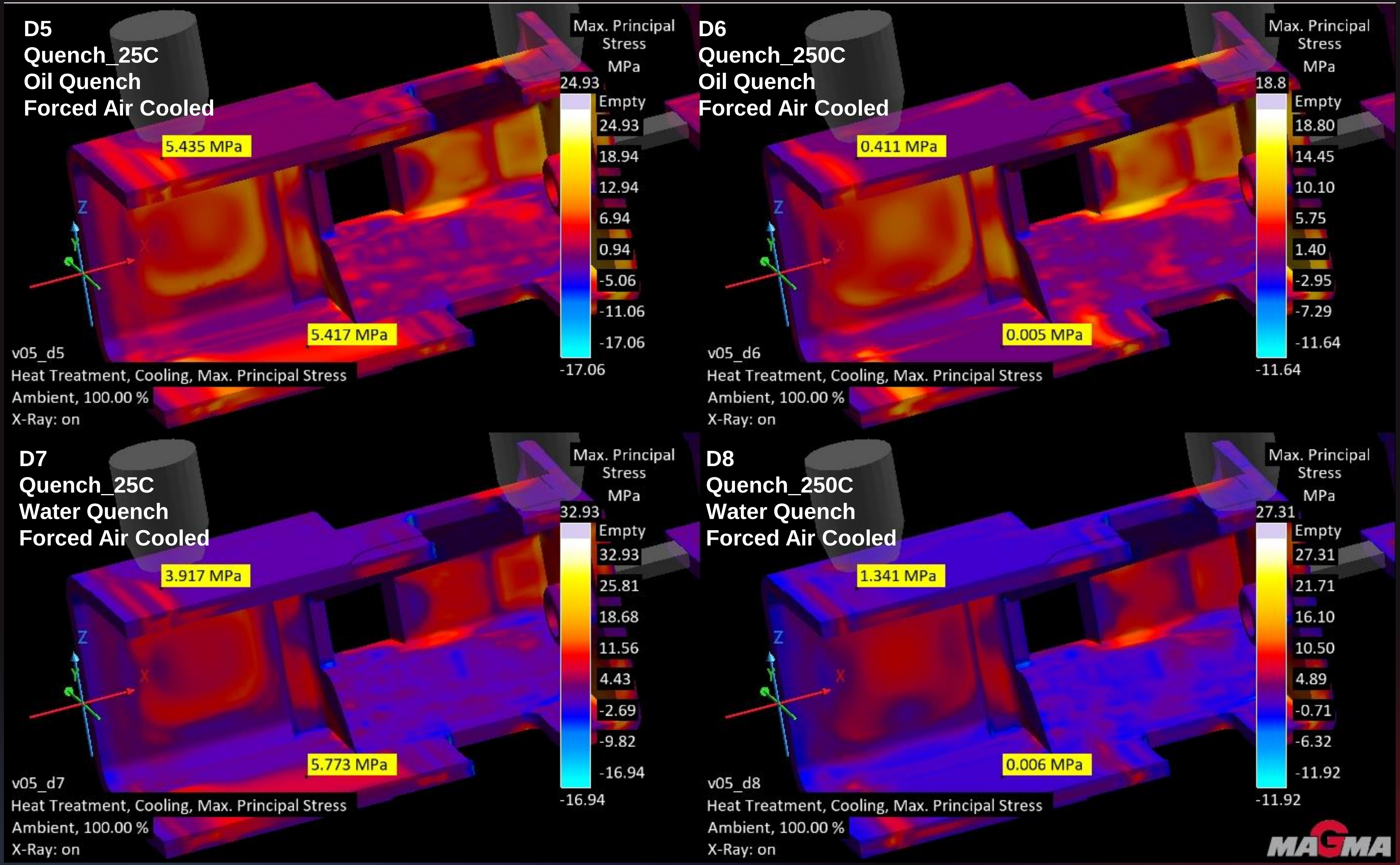


Finding –

d1 & d3 quenched in low temp fluids having more max principal stress

Results Assessment

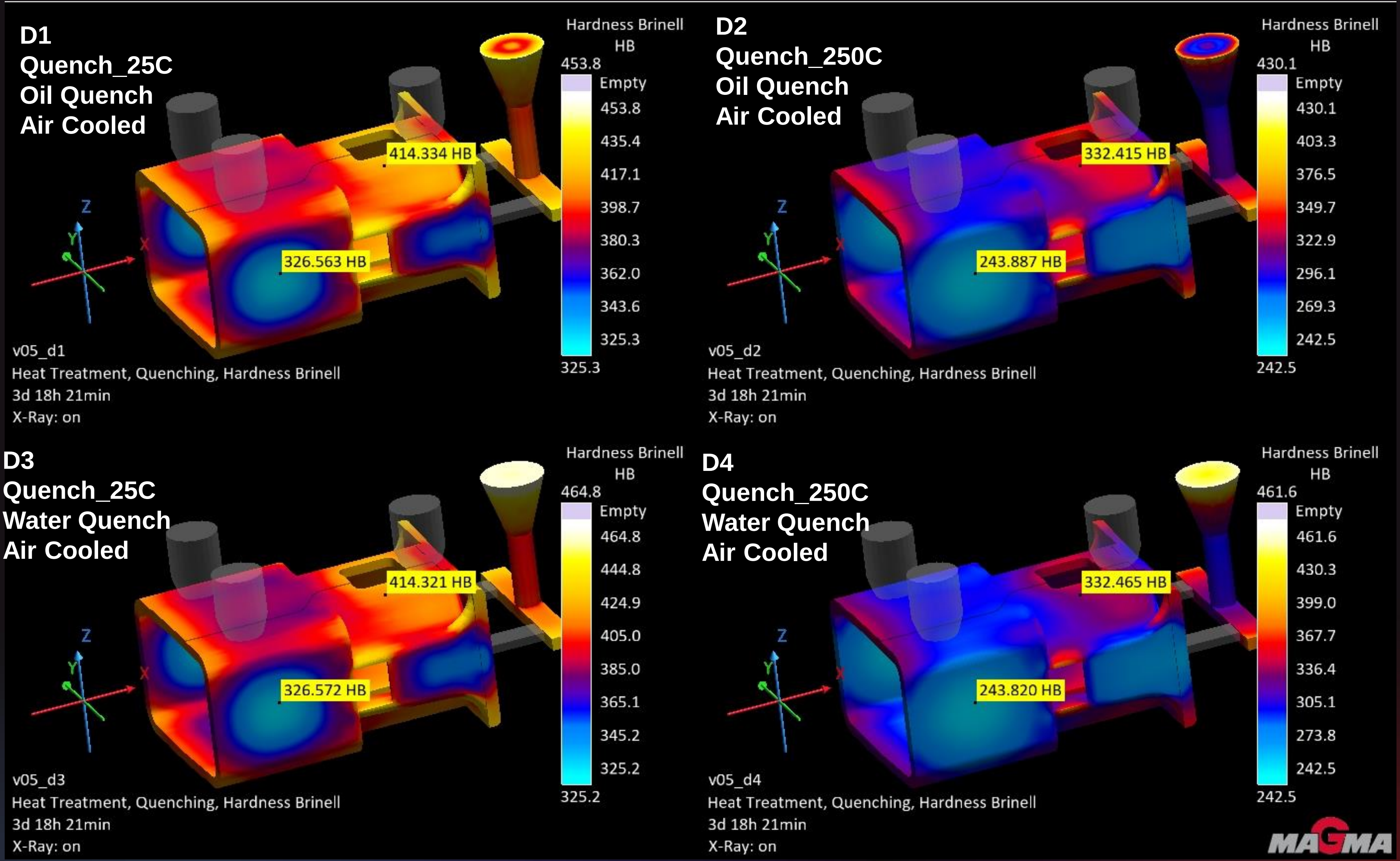
- Max Principal Stresses (Heat Treatment)



Finding – similarly d5, d7 having more max principal stress

Results Assessment

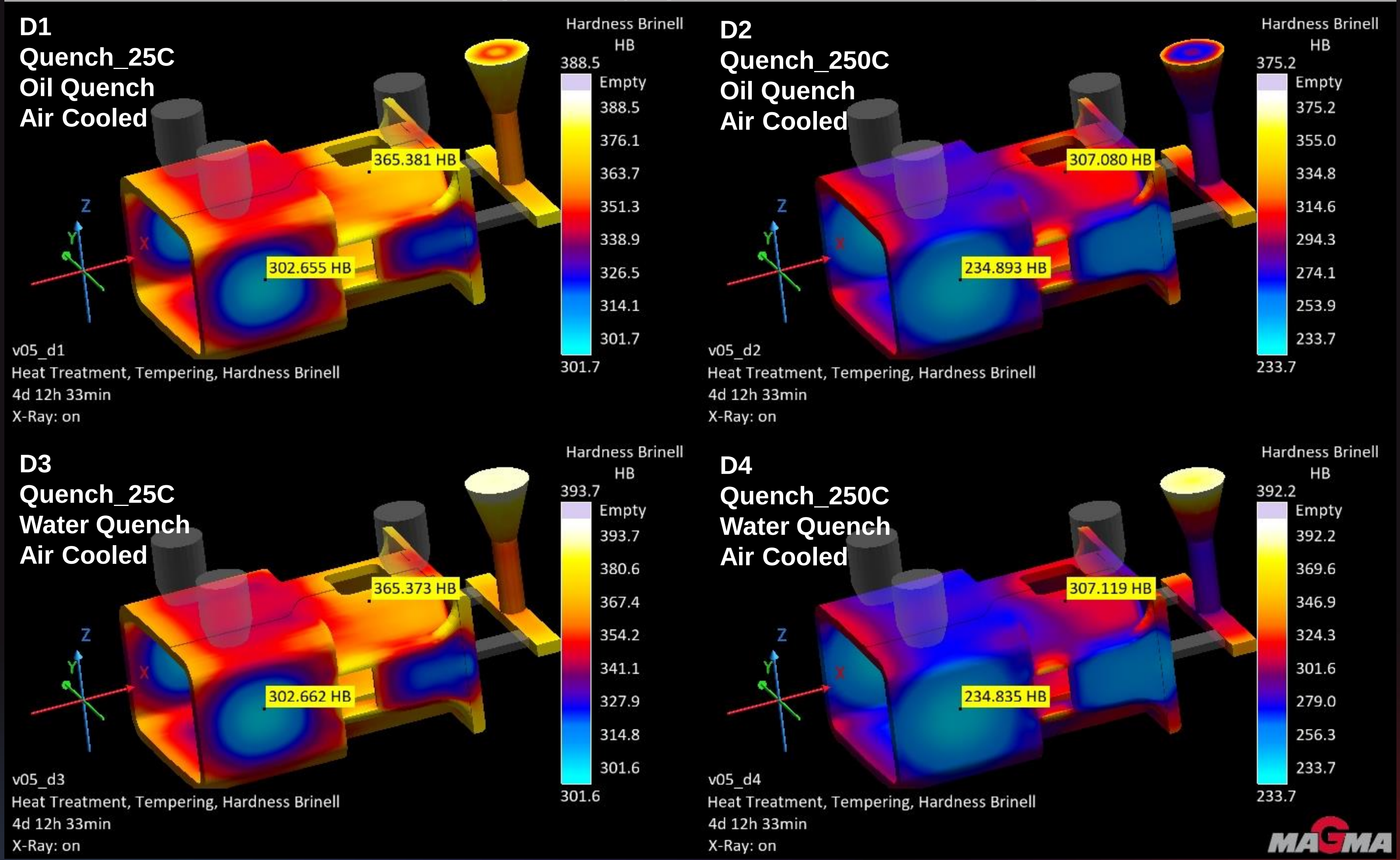
Hardness Brinell, Quenching (Heat Treatment)



Finding –
Again quenching medium temperature affecting Hardness as more rapid cooling leading to higher hardness

Results Assessment

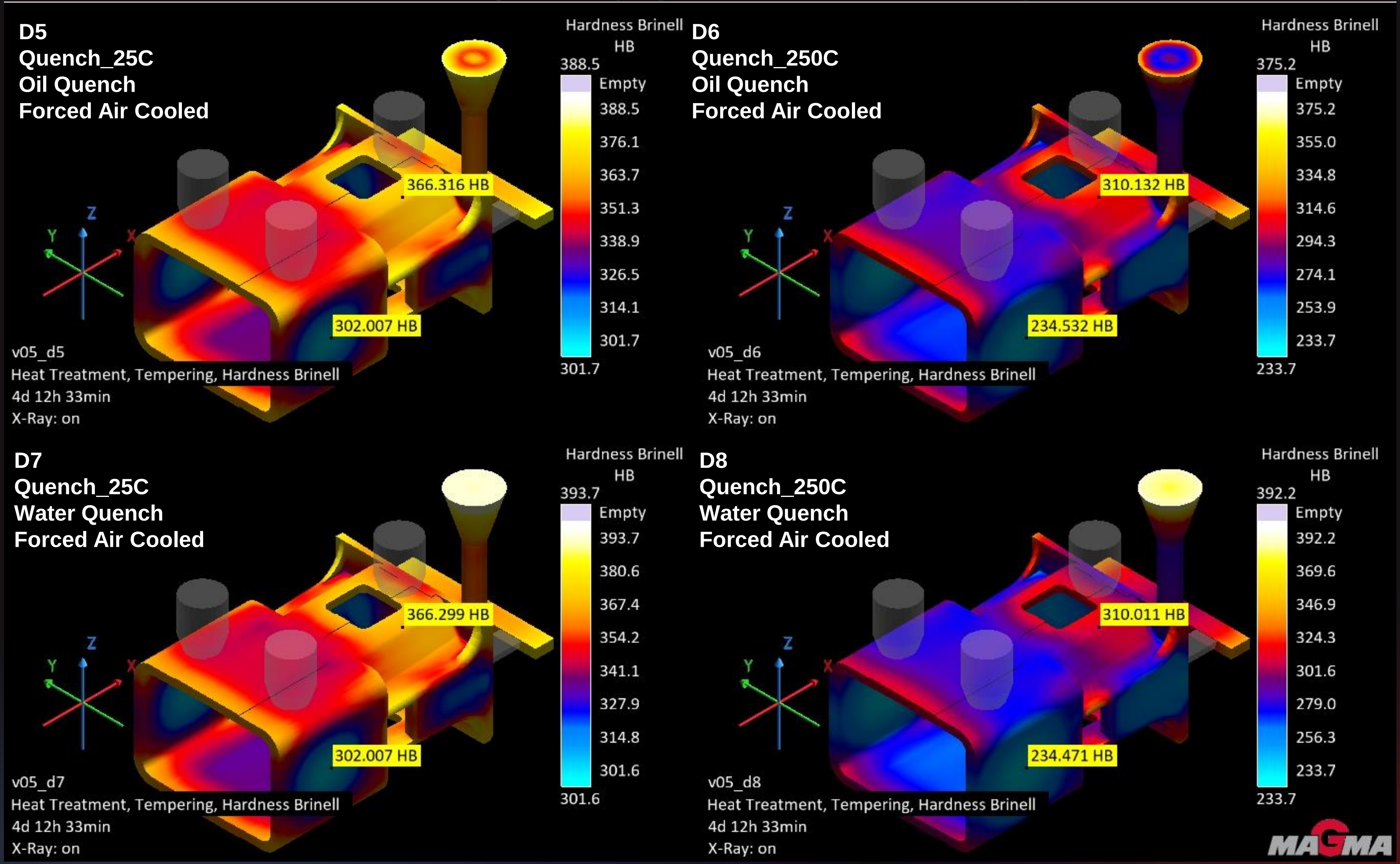
Hardness Brinell, Tempering (Heat Treatment)



Finding –
Tempering definitely reducing hardness as compensation to toughness

Results Assessment

Hardness Brinell, Tempering (Heat Treatment)

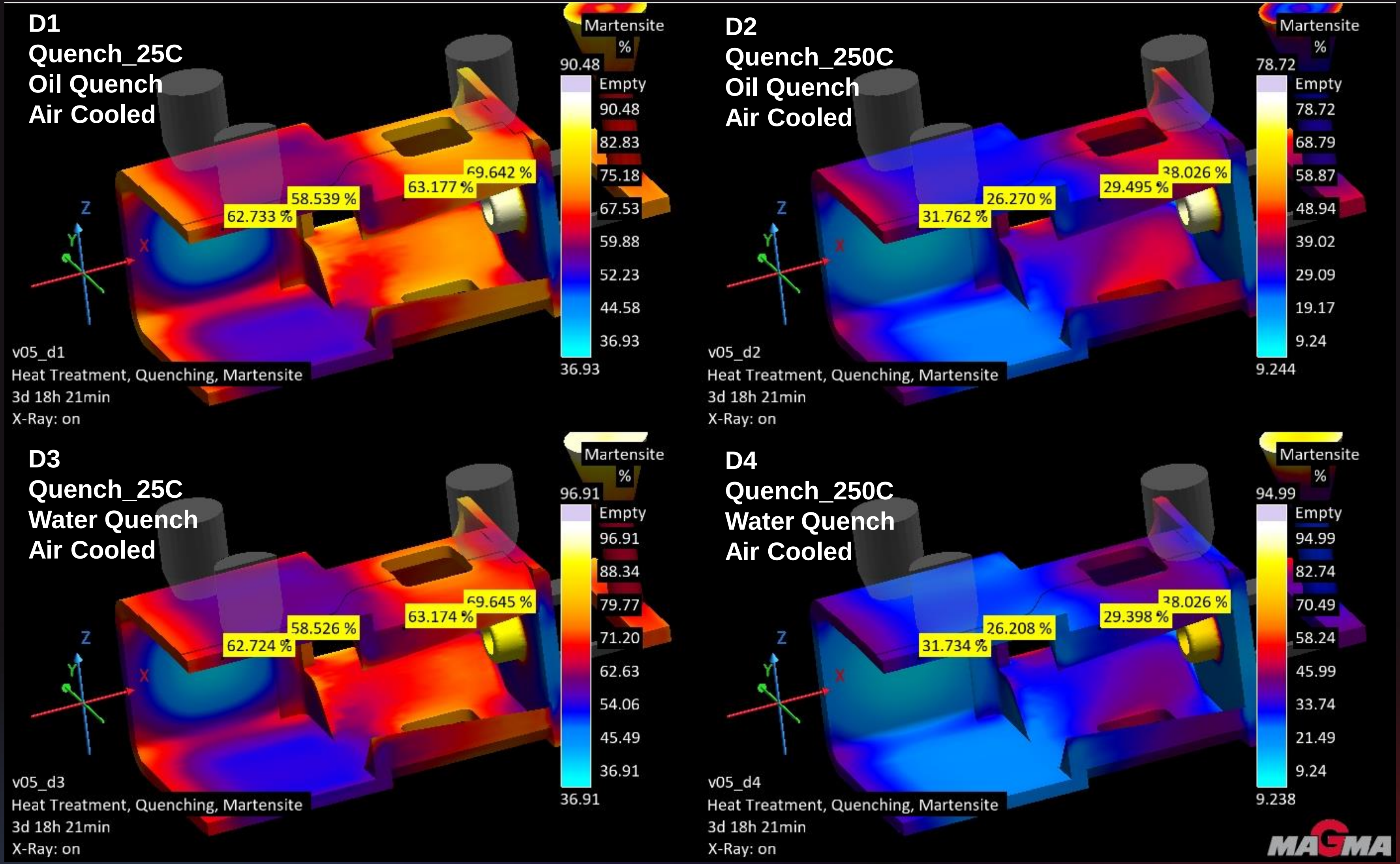


Finding –

Tempering definitely reducing hardness as compensation to toughness while tempering cooling variation not showing much effect

Results Assessment

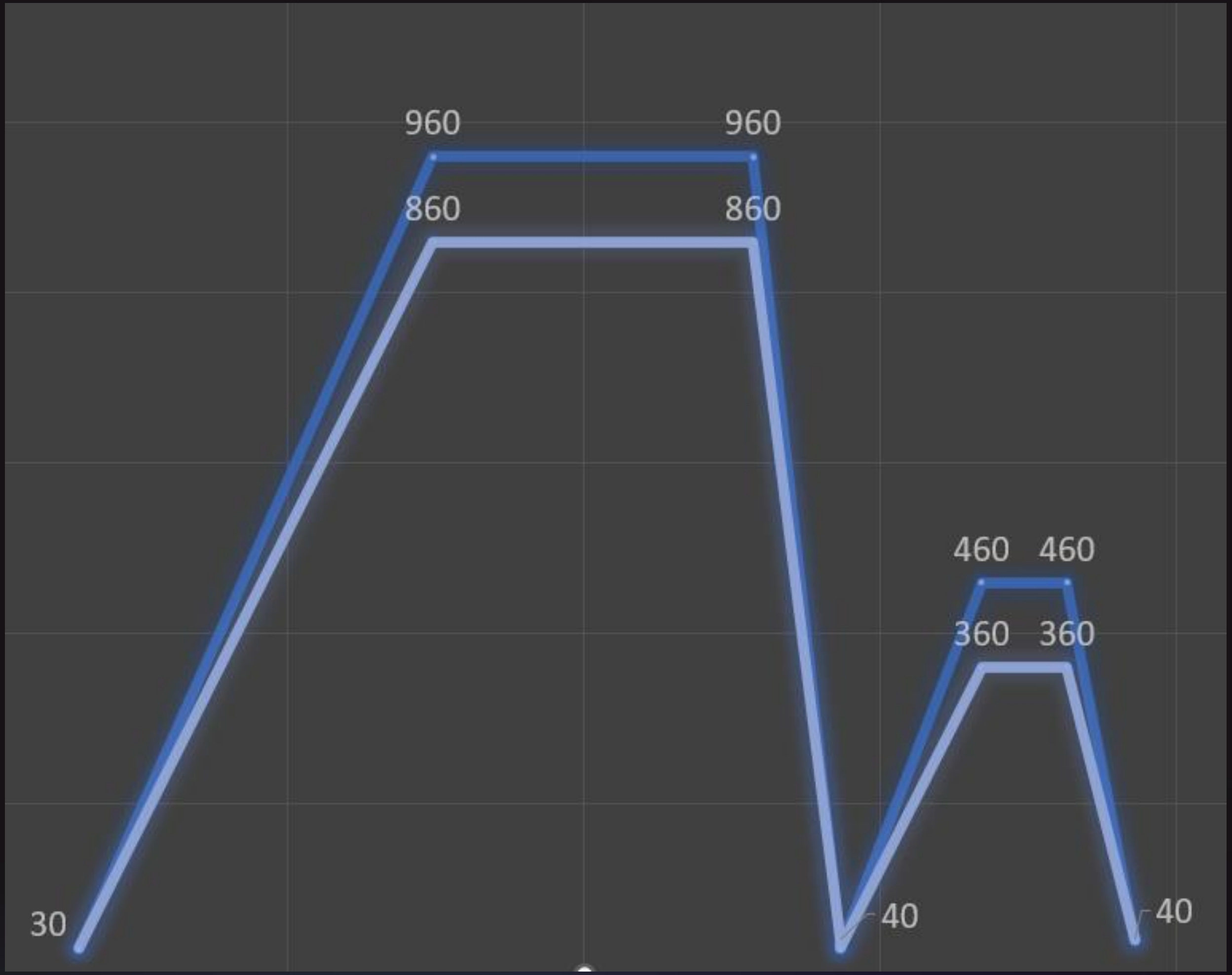
Microstructure (Heat treatment)

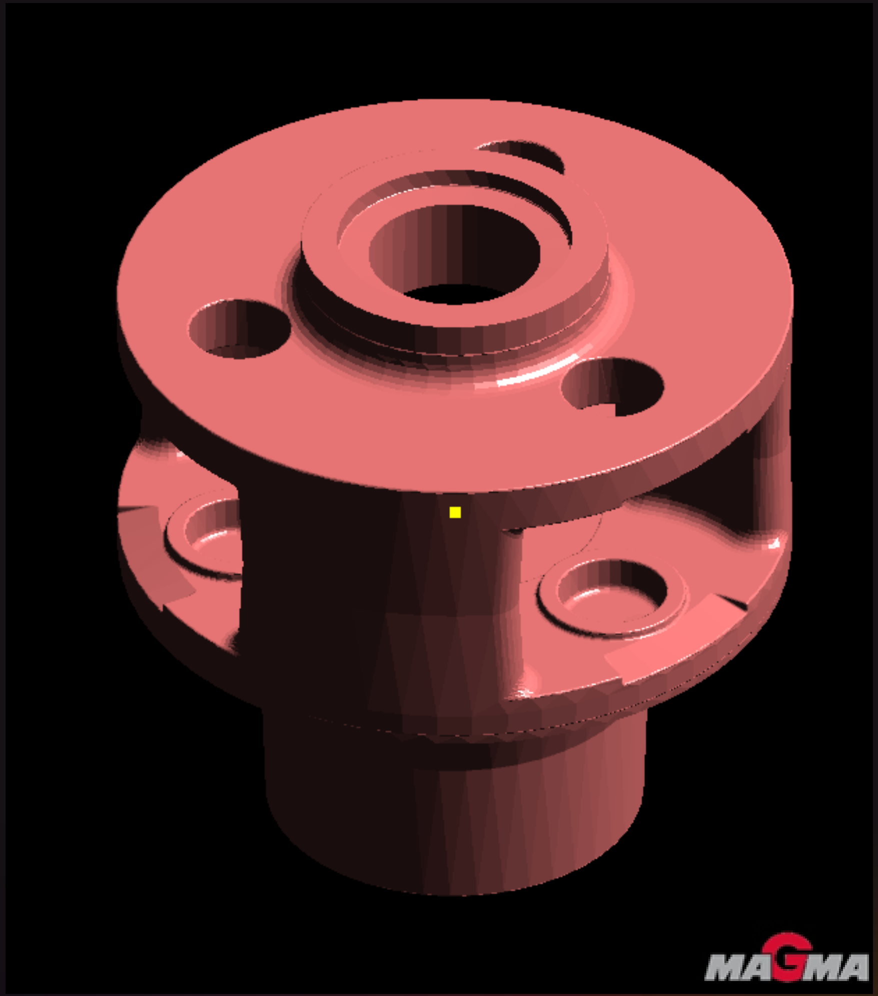


Finding –
More martensite formation as a result of rapid cooling in comparison of cooling in hot fluids

Is that all we can do?

Optimizing Soaking Temperature





Optimizing Soaking Temperature

Design Variables

	Design Variable	Dataset List	Dependency
☑	001 Austenitization - Temperature History	User/Steel_Oven_860C User/Steel_Oven_960C	<None>
☑	003 Tempering - Temperature History	User/Steel_Temper_360C User/Steel_Temper_460C	<None>

Design ID	001 Austenitization - Temperature History	003 Tempering - Temperature History
1	User/Steel_Oven_860C	User/Steel_Temper_360C
2	User/Steel_Oven_960C	User/Steel_Temper_360C
3	User/Steel_Oven_860C	User/Steel_Temper_460C
4	User/Steel_Oven_960C	User/Steel_Temper_460C

DoE (4 Designs)-

- Austenitizing Medium at two different temp
- Quenching Medium at two different temp

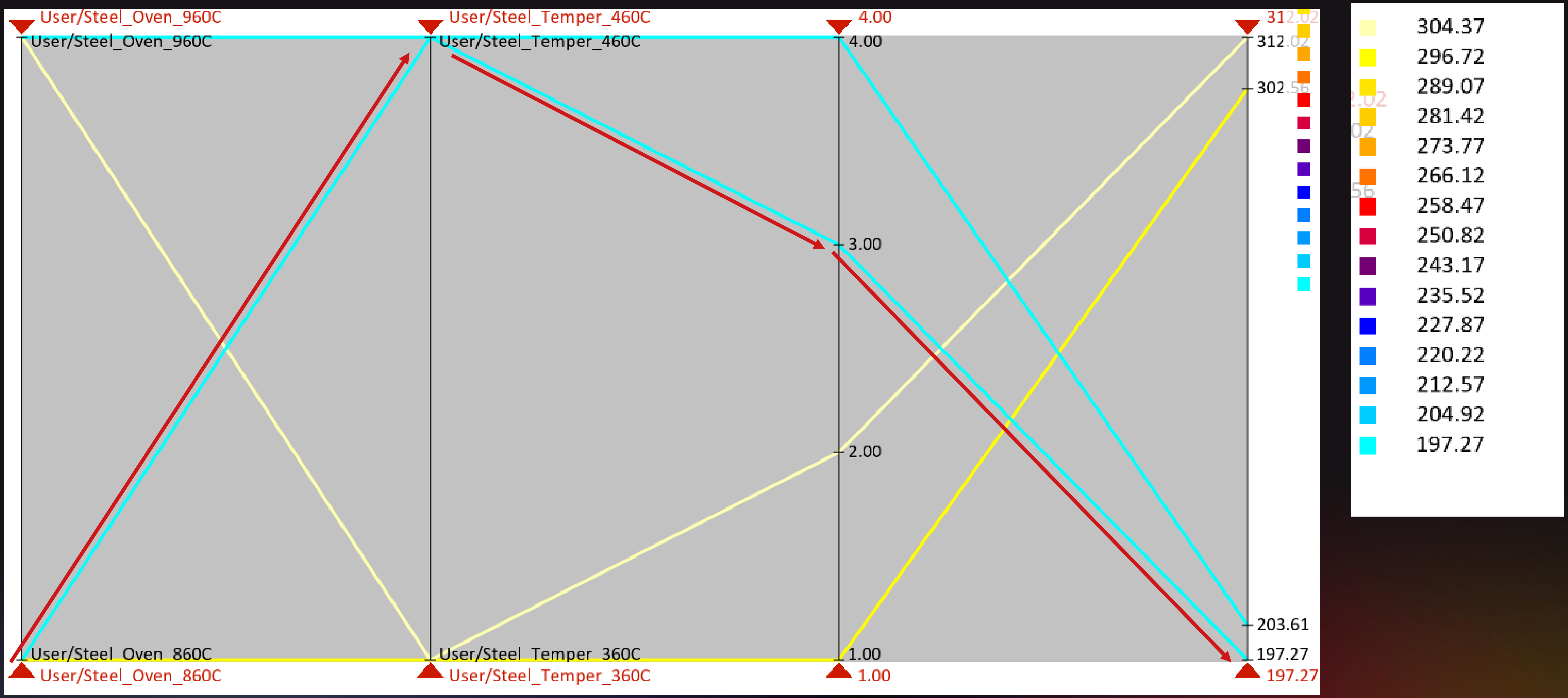
Assessment of DoEs

Austenitization Temperature History

Tempering Temperature History

Design ID

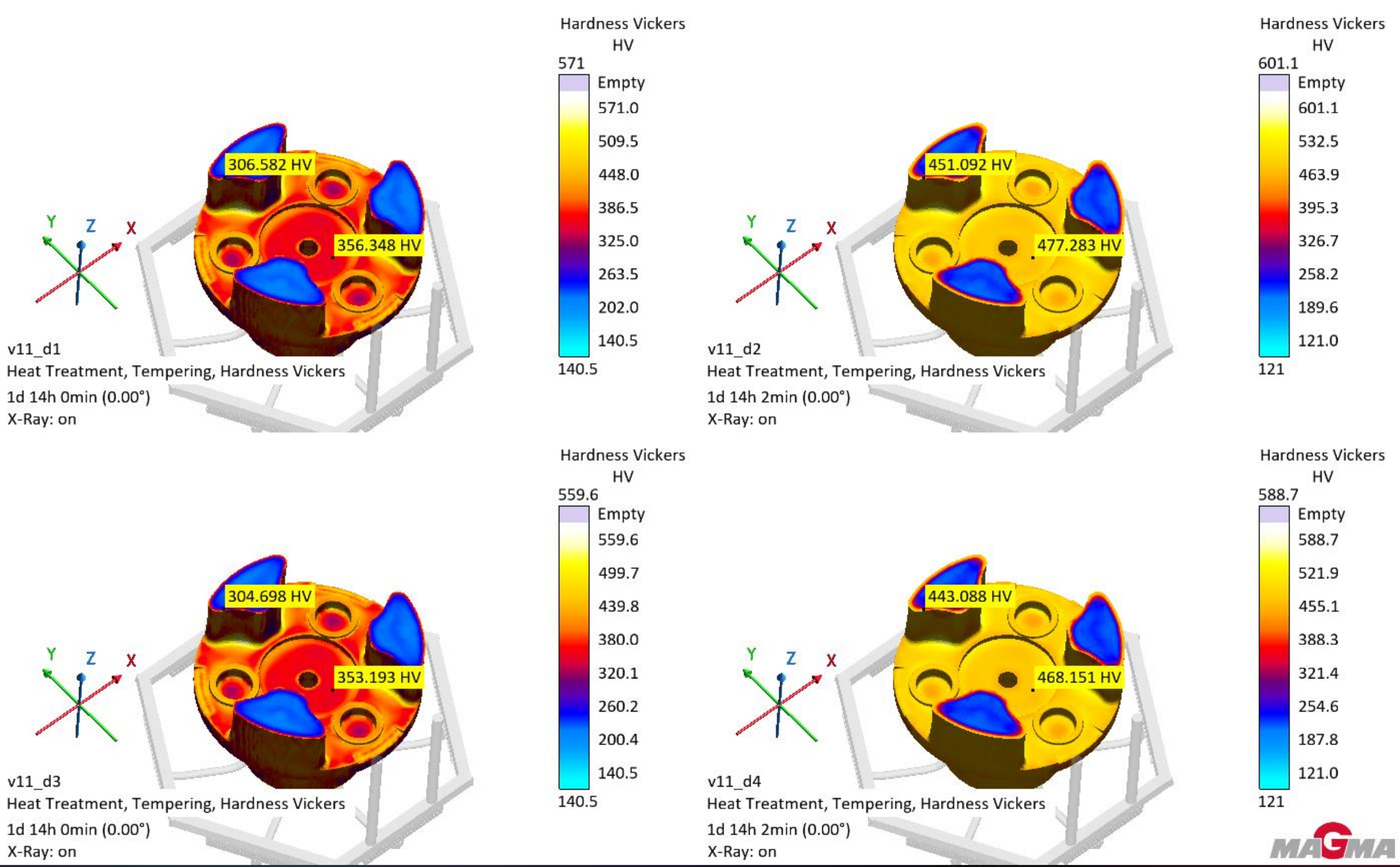
Reduced Max. Principal Stress (Heat Treatment)



ACT & CHECK IMPROVEMENTS

Results Assessment

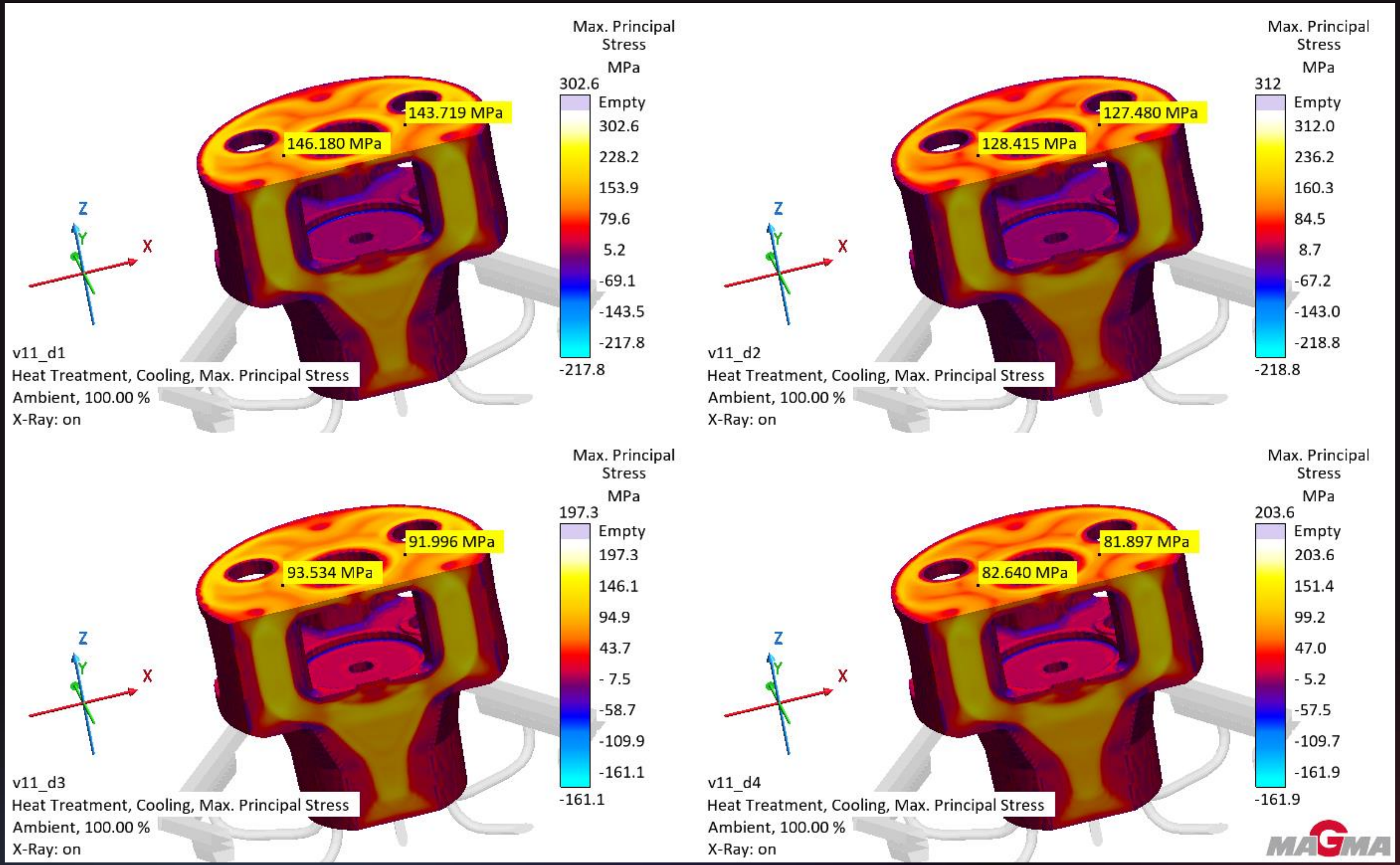
(Hardness after tempering)



Finding –
Quenching at high temperature increased the hardness considerably, while tempering temperature change showing less effects

Results Assessment

(Stresses)

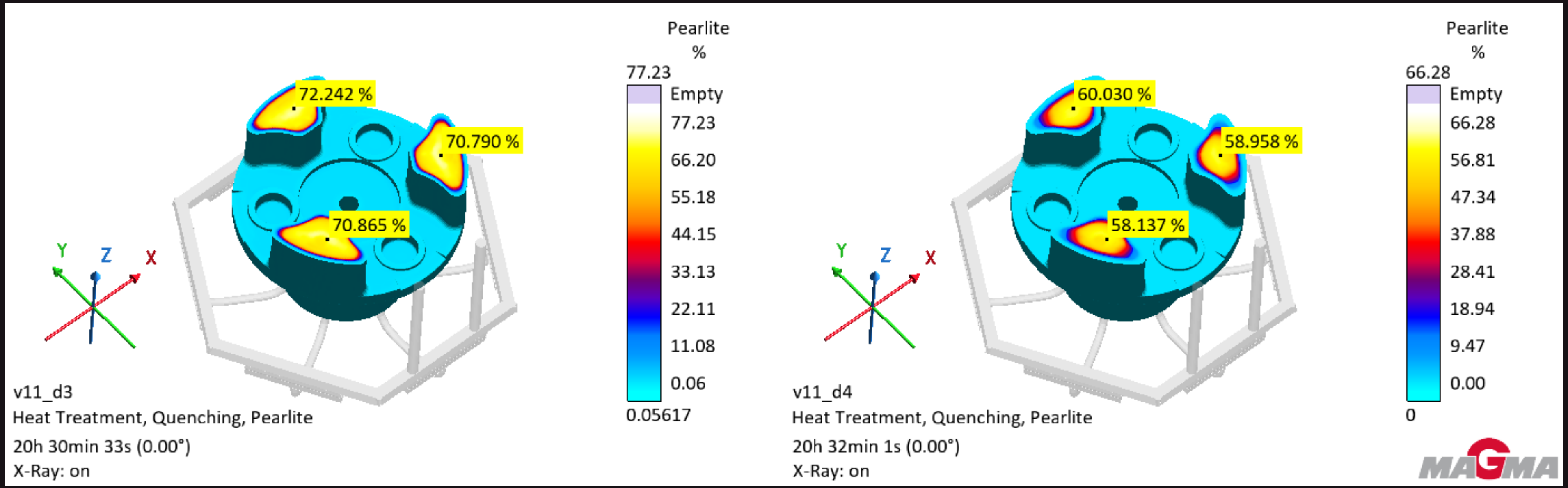


Finding –

d3, d4 tempered at 460°C shows significant improved stresses in comparison of d1,d2 tempered at 360°C

Results Assessment

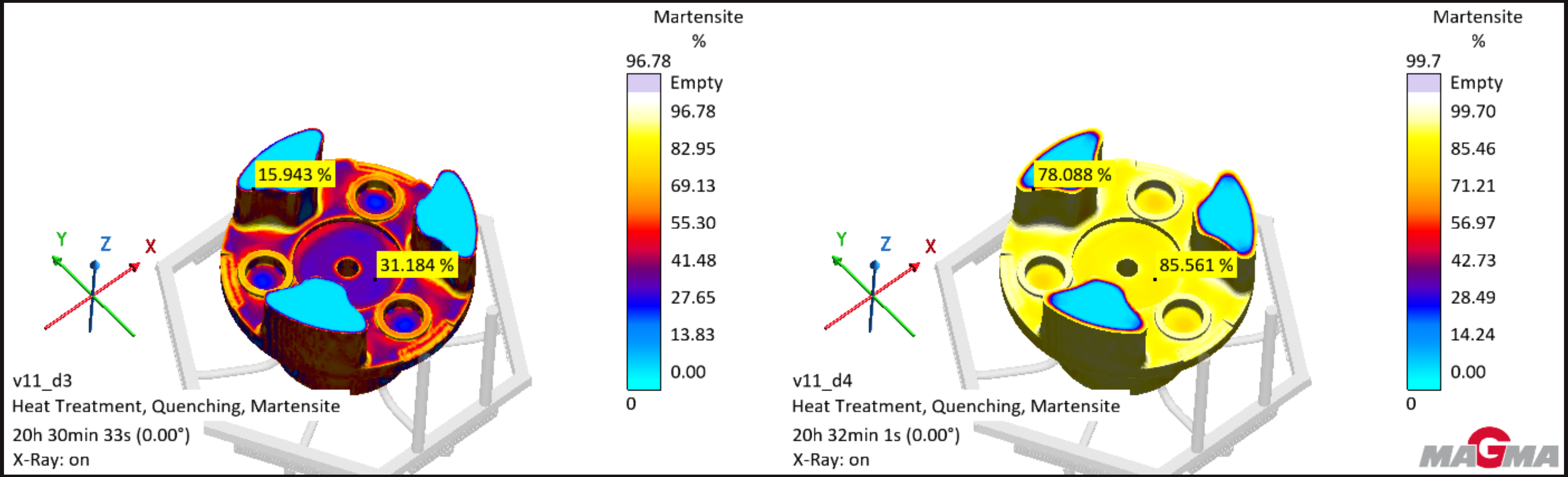
(Pearlite Formation after Quenching)



Finding –
Quenching at low temperature (860 °C) causes more pearlite formation in core regions

Results Assessment

(Martensite formation after quenching)



Finding –
Queching at high temperature (960 °C) Causes more martensite formation at outer and sub-surfaces.

Thank you for your attention.