Modeling of Phase Transformation in Induction Hardening

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Abstract: Mechanical properties of machined components are controlled by inducing phase transformations in the outer layer of the materials. Induction hardening is one such manufacturing process where the surface hardness is enhanced while the core is retained with the original structure and characteristics. In this study, a mathematical model had been developed to predict the hardness and the volume fraction of martensite present in the hardened surface. Experiments applying induction hardening were conducted on the following specimen materials AISI 1040, AISI 4140, AISI 4340, AISI 1055, AISI 6150 and AISI 9255. The microstructures obtained from the experiment showed a moderate phase transformation of austenite to martensite. The hardness and the volume fraction of martensite estimated from the experiments were found to match the results of mathematical modeling as well as the theoretical model using regression analysis.

Keywords: Modeling, phase transformation, induction hardening, volume fraction, validation.

1. INTRODUCTION

Induction hardening is an important manufacturing process to control the mechanical properties of metal parts where surface hardness is enhanced while the core retains the original structure and toughness characteristics [1]. This is possible by inducing suitable phase transformation in the outer layer of the material. Two types of modification occur when phase transformation takes place while quenching. The first type called metallurgical interaction is kinetic modification which sometimes leads to a different morphology in the phase produced. The second type (commonly called transformation plasticity) is a mechanical modification related to the progress of transformation, and takes place when plastic deformation occurs under [2] stresses lower than the yield stress of the material (Denis, S., *et al.*, 1985).

The importance of thorough knowledge of the transformation characteristics of steel in the solution of heat treatment and steel selection problems and in the explanation of stress related phenomena has long been realized. It is obvious that for the quick decisions, which are the order of the day, metallurgists and materials engineers cannot undertake expensive and time-consuming metallographic experiments to determine volume fraction of martensite and maximum hardness value obtainable, considering heating and cooling curves relevant to their actual technology and the work material. Instead, they must turn to the literature, but unfortunately the data found, i.e. the chemical composition, grain size, heating and cooling curves indicated on the existing diagrams, differ from those required [3,4]. It is felt that the most direct assistance to the materials engineers employed in heat treatment industry is to provide them with solution in the form of mathematical models to predict the hardness and volume fraction of martensite at any point in the Induction hardened zone of a given steel component with any composition within the allowed range for the induction hardening steel type. Hence, in this paper a mathematical modeling has been developed to predict the volume fraction of martensite and hardness for the materials considered in the current research [5].

2. MODELING OF INDUCTION HARDENING

Modeling of induction hardening is a complex issue which involves numerically solving the Maxwell's equations for electromagnetic field around workpiece, coupled with heat transfer principles for modeling the product thermal process (Nemkov, V.S., and Goldstein, R., 1999). The system is inevitably highly nonlinear because of temperature dependent material properties of workpiece. In the past, more attention of numerical simulation was paid to modeling only certain aspects of the induction hardening problem; little effort has been paid to model the integrated process from heating to final hardening. Numerical simulation of the magnetic field was ever conducted. They provided valuable analysis for the magnetic vector potential which was a very important parameter for eddy current and Joule heat determination. Simulation of induction heating has been carried out and provided models for solving coupled electromagnetic/thermal analysis. Recently, quenching and phase transformation process has been simulated. And the Koistinen-Marburger law and Avrami equation was applied for determination of volume fraction of micro-constituents formed in the quench cooling process. However, few studies have been found to predict the hardness distribution using numerical simulation.

Jiankun Yuan *et al*., (2003) [6] developed an integrated FEA based modeling system with the capabilities to simulate the electromagnetic field induced heating process, austenite state holding processes, and severe quenching processes. This modeling system helps in determining volume fraction of micro constituent such as martensite formed in the quench cooling process, and final hardness distribution pattern in work piece. However, there is a restriction in using this model because this model involves analysis of interaction of

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continuous cooling curve with Temperature –Time – Transformation diagram. It must be remembered that cooling curves are difficult to obtain in Induction hardening applications. This is because the exact conditions are difficult to duplicate in the laboratory (Scott Mackenzie., 2002).

This paper deals with the model, which may be considered as an extension of Yuan model, developed to predict the volume fraction of martensite theoretically. A Regression model has also been developed to estimate the Hardness in HRA for steel materials, AISI 1040, AISI 4140, AISI 4340, AISI 1055, AISI 6150 and AISI 9255. These models overcome the drawbacks in the modeling system explained above. Experimental validation of the developed model has also been presented here.

3. MATHEMATICAL MODEL TO PREDICT THE HARDNESS

In order to develop the mathematical model to predict the hardness and volume fraction of martensite for Induction hardening of steel materials (G1 – Material and G2 – Material), Induction hardening experiments have been conducted.

Table **1** shows the details about the operating conditions and the materials.

Table **2** shows the experimental results in the 3^3 Design Matrix for the G1 and G2 Induction hardening rack materials respectively.

Regression analysis has been carried out using MATLAB and the Regression equations (Equation to predict the hardness of the materials) have been found and the same are given below:

3.1. Model Regression Analysis

AISI 1040

Coeff =

1.0000	5.5000	1.3400	15.0000	80
1.0000	5.5000	1.3400	17.5000	78
1.0000	5.5000	1.3400	20.0000	79
1.0000	5.5000	1.7200	15.0000	80
1.0000	5.5000	1.7200	17.5000	78
1.0000	5.5000	1.7200	20.0000	82
1.0000	5.5000	2.1400	15.0000	83
1.0000	5.5000	2.1400	17.5000	74
1.0000	5.5000	2.1400	20.0000	81
1.0000	7.0500	1.3400	15.0000	74
1.0000	7.0500	1.3400	17.5000	78
1.0000	7.0500	1.3400	20.0000	77
1.0000	7.0500	1.7200	15.0000	78
1.0000	7.0500	1.7200	17.5000	74
1.0000	7.0500	1.7200	20.0000	76
1.0000	7.0500	2.1400	15.0000	78
1.0000	7.0500	2.1400	17.5000	74
1.0000	7.0500	2.1400	20.0000	78
1.0000	8.5000	1.3400	15.0000	69
1.0000	8.5000	1.3400	17.5000	65

Table 1. Experimental Conditions and Work Materials

S. No.	Variables	Unit	Notation	Levels Actual			Code		
				Low	Medium	High	Low	Medium	High
1	Power potential	kW/inch^2	P	5.5	7.05	8.5	L1	L2	L3
2	Scan speed	m/min	S	1.34	1.72	2.14	L1	L2	L3
3	Quench flow rate	Litres/min	Q	15	17.5	20	L1	L2	L3
Design of Experiment: Factorial Design of Experiment with 3^3 Design matrix.									
Regression analysis.									
Material: Group 1 (Carbon content ranging from 0.35 -0.45%, Maximum HRC possible 60).									
Group 2 (Carbon content ranging from 0.45 – 0.6%, Maximum HRC possible 65).									

Material	Steel Designation	Chemical Composition in Percentage
Group 1	AISI 1040	C-0.35%, Si-0.10%, Mn-0.60% S&P each 0.06%
	AISI 4140	C-0.35%, Si-0.10%, Mn-0.50%, Cr-0.90, Mo-0.20% S&P each 0.05%
	AISI 4340	C-0.35%, Si-0.10%, Mn-0.45%, Cr-0.90%, Mo-0.20%, Ni-1.30% S&P each 0.05%
Group 2	AISI 1055	C-0.45%, Si-0.10%, Mn-0.50%, S&P each 0.06% (max)
	AISI 6150	C-0.50%, Si–0.50%, Mn-0.50%, Cr-0.80%, V-0.15% S&P each -0.05 (each)
	AISI 9255	C-0.55%, Si–1.50%, Mn-0.70%, S&P each -0.05 (max)

Table 2. **Experimental Results for G1 and G2 Materials for Induction Hardening**

S. No.	P	S	Q	Hardness in HRA for G1 Materials			Hardness in HRA for G2 Materials		
				AISI 1040	AISI 4140	AISI 4340	AISI 1055	AISI 6150	AISI 9255
1	5.5	1.34	15	80	83	82	84	83	84
2	5.5	1.34	17.5	78	81	83	83	82	80
3	5.5	1.34	20	79	80	78	84	80	84
4	5.5	1.72	15	80	78	80	80	80	83
5	5.5	1.72	17.5	78	76	78	80	84	82
6	5.5	1.72	20	82	78	79	84	79	81
7	5.5	2.14	15	83	82	80	81	80	83
8	5.5	2.14	17.5	74	80	77	83	84	82
9	5.5	2.14	20	81	82	80	82	84	84
10	7.05	1.34	15	74	74	74	78	78	78
11	7.05	1.34	17.5	78	72	72	80	70	75
12	7.05	1.34	20	77	76	73	78	73	71
13	7.05	1.72	15	78	78	70	70	70	70
14	7.05	1.72	17.5	74	75	75	77	76	77
15	7.05	1.72	20	76	78	75	80	77	80
16	7.05	2.14	15	78	75	74	75	73	80
17	7.05	2.14	17.5	74	75	72	73	75	78
18	7.05	2.14	20	78	74	75	73	74	75
19	8.5	1.34	15	69	69	75	78	78	73
20	8.5	1.34	17.5	65	67	69	70	70	73
21	8.5	1.34	20	67	65	67	68	67	70
22	8.5	1.72	15	64	68	68	70	68	68
23	8.5	1.72	17.5	62	68	63	74	64	69
24.	8.5	1.72	20	63	70	65	70	67	70
25	8.5	2.14	15	68	66	68	67	70	67
26	8.5	2.14	17.5	67	68	66	69	69	69
27	8.5	2.14	20	65	68	64	72	70	74

1.0000 8.5000 1.3400 20.0000   67

1.0000 8.5000 1.7200 15.0000   64

1.0000 8.5000 1.7200 17.5000   62

1.0000 8.5000 1.7200 20.0000   63

1.0000 8.5000 2.1400 15.0000   68

1.0000 8.5000 2.1400 17.5000   67

1.0000 8.5000 2.1400 20.0000   65

The coefficients for the formation of hardness equation are,

107.2820

-4.5995

0.1873

-0.0889

Therefore, for AISI 1040,
$$Y_H = 107.2820 - 4.5995P + 0.1873S - 0.0889Q \qquad (1)$$

For AISI 4140,
$$Y_H = 102.33421 - 4.0993P + 0.4140S + 0.0001Q \qquad (2)$$

For AISI 4340,
$$Y_H = 111.5611 - 4.1474P - 2.3059S - 0.2889Q \qquad (3)$$

For AISI 1055,
$$Y_H = 106.7885 - 3.8179P - 3.8671S + 0.1778Q \qquad (4)$$

For AISI 6150,
$$Y_H = 108.2939 - 4.1947P - 0.2082S - 0.2000Q \qquad (5)$$

For AISI 9255,
$$Y_H = 102.9862 - 4.0.759P + 0.6014S + 0.0667Q \qquad (6)$$

4. MATHEMATICAL MODEL TO PREDICT THE VOLUME FRACTION OF MARTENSITE

To predict the volume fraction of marteniste for Induction hardening of materials (G1 and G2 materials) mathematical model has been developed as a part of the current research work. For this modeling work, a computer model given by Yuan *et al*., (2003), has been taken into account and extended to make it suitable for the present research work. Yuan *et al*., (2003), developed the following mathematical model (equation 7) to predict HRC and Volume fraction of martensite using FEM for the Induction hardened components.

$$HRC = afm^2 + bfm + c \qquad (7)$$

where a, b and c are constants and dependent only on carbon content in the materials. Further, it is given that for the materials,

AISI 1070 (0.65% Carbon)   a = 80.91   b = -97   c = 81.61

AISI 1053 (0.55% Carbon)   a =77.84   b = -90.85 c = 75.28

Equation 7 can be rewritten in the form of

$$afm^2 + bfm = HRC - c \qquad (8)$$

$$fm (afm + b) = HRC - c \qquad (9)$$

In general for the Induction hardened medium carbon alloy steels the hardness value lies in the range 56 – 65 HRC and volume fraction of martensite between 0.9 and 1.0 (Thelning, K.E., 1984). Hence it is assumed that fm = 1, therefore from the equation 9, it is obtained that,

$$afm + b = HRC - c \qquad (10)$$

The equation 10 is used in the model development. Equation 10 becomes,

$$fm = (HRC - c - b) / a \qquad (11)$$

On substituting a, b, and c values of 0.55% carbon steel material (AISI 1053) in the equation 11, we get

$$fm = [(HRC) - 75.28 + 90.25] / 77.85 \qquad (12)$$

For a maximum hardness of 65 HRC the volume fraction of martensite should be equal to one. The following calculations will justify the above said statement.

$$fm = [65 - 75.28 + 90.25] / 77.85 = 1.027 \quad (approximately = 1)$$

Therefore, the equation 12 can be rewritten as

$$fm = [(HRC) max - 75.28 + 90.25] / 77.85 (HRC) max = 65 \qquad (13)$$

In the present analysis the process variables Power potential (P), Scan speed (S) and Quench flow rate (Q) of Induction hardening process are taken for the study of phase transformation, model development, simulation and validation. Further, it is construed that there is a definite relation between the above said process variables with the hardness and volume fraction of martensite of the Induction hardened materials.

In order to develop a mathematical model to predict the volume fraction of marteniste for the materials (Group 2 – carbon content 0.5 – 0.6%) using the above mentioned process variables an analysis has been carried out by replacing the constants a, b and c with the optimal process variables P, Q and S (P = 5.5 kW/inch^2, S = 1.72 m/minutes and Q = 15 litres/minutes) obtained in the optimization study and it is found that,

Constant   c = 75.28 = 13.68P

                  b = 90.85 = 6.05Q

                  a = 77.85 = 45.26S

Therefore, the mathematical model to find the volume fraction of martensite with the process variables P, Q and S is derived as,

$$fm = [(HRC) max - 13.68P + 6.05Q] / 45.26S \qquad (14)$$

(or)

$$fm = \{[(HRC) max - 13.68P + 6.05Q] \, 0.02206S^{-1}\} \qquad (15)$$

For the Group 1 materials (carbon content 0.35 – 0.45%) the hardness lies in the range 56 – 60 HRC (Thelning, K.E., 1984) [7]. By extrapolation and interpolation it is found that the constants a, b and c for the Group 1 materials as a = 74.77, b = -83 and c = 68.95.

In order to verify the obtained constants the following calculation is carried out using the equation 11, by assuming HRC as 60 when fm = 1.

$$fm = (HRC - c - b) / a$$

$$fm = (60 - 68.95 + 83) / 74.77$$

$$fm = 0.9903$$

It shows that the obtained values of a, b and c are absolutely correct. By following the same procedure as that adopted in the development of volume fraction of martensite of Group 2 materials, the mathematical model to predict the 'fm' for the Group 1 materials has been obtained and presented below.

$$fm = \{[(HRC) max - 11.96P + 5.27Q] / 43.5S\} \qquad (16)$$

(or)

$$fm = \{[(HRC) max - 11.96P + 5.27Q] \, 0.0230S^{-1}\} \qquad (17)$$

Thus the mathematical models(equations 1,2,3,4,5, and 6- pertaining to HRA; 14(or) 15 and 16 (or) 17 – pertaining to fm) developed are used to predict the volume fraction of martensite and hardness respectively without conducting the trials on Induction hardening furnace [8,9].

5. VALIDATION OF THE MODEL

In this study Induction hardening is carried out on AISI 1040, AISI 4140, AISI 4340, AISI 1050, AISI 6150 and AISI 9255. These types of steel materials chosen for the studies because such steels are typical candidate materials for a variety of automobile components especially Rack that require local hardening [10]. The theoretical simulations (results obtained from the model developed) are compared with results produced experimentally. Koistinen equation 18 is used to find the volume fraction of marteniste theoretically,

$$fm = 1 - exp \{-0.011 [Ms - Tq]\} \qquad (18)$$

where, Ms – starting temperature of marteniste formation (Rajan, T.V., *et al*., 1998) [11]

Ms (°C) = 561 -474(%C) – 33(%Mn) -17(%Ni) -17(%Cr)-21 (%Mo)   (19)

Tq – Quenchant temperature at which fraction of martensite is formed

For the material AISI 1040, the Ms temperature is found as per the following procedure

AISI 1040 - Carbon = 0.35%, Si = 0.1% and Mn = 0.6%,

Ms (°C) = 561 -474(%C) – 33(%Mn) -17(%Ni) -17(%Cr)- 21(%Mo)

$\qquad$ = 561 – 474 (0.35) – 33 (0.6)

$\qquad$ = 375.3°C

Similarly, for the other materials also the Ms Temperature is calculated and given in Table **3**.

Table 3.   Ms Temperature for G1 and G2 Materials

AISI Grade	Ms (°C)
1040	375.3
4140	359.1
4340	338.65
1055	331.2
6150	293.9
9255	277.2

Random trials are carried out by varying the process variables P, Q and S by subjecting the G1 and G2 materials in the Induction hardening furnace and the temperature Tq (Quenchant temperature at which fraction of martensite is formed) is measured using thermocouple. Hardness of the each specimen is measured using Rockwell hardness tester in HRA.

The volume fraction of marteniste (experimental) is found as per the calculation given below for the material AISI 1040, (Ms = 375.3 from Table **3** and Tq = 65°C through measurement when P = 5.5kW/inch^2, Q = 15 litres /min and S = 1.72 m /minutes)

fm = 1- exp {-0.011 [Ms – Tq]

fm = 1 – exp {-0.011 [375.3 – 65]}

fm = 0.9670

The volume fraction of martensite (theoretical) is found as per the details given below using the model developed for AISI 1040 steel material with the values of process variables used in the trials.

fm = {[(HRC) max – 11.96P+5.27Q] / 42.2S}

fm={[60-12*5.5+5.3*15]/42.2*1.72}

fm={[60-66+79.05]/72.6}

fm=1.006

The hardness value (theoretical) is found by using the Regression model equation.

Regression equation for the AISI 1040

Y_H = 107.2820-4.5995P+0.1873S-0.0889Q

where, P=5.5, S=1.72 and Q=15

On substitution theoretical, Y_H =107.2820 - 4.5995*5.5+0.1873*1.72-0.0889*15

$\qquad$ = 107.2820-25.3+0.322-1.3

$\qquad$ = 81 HRA

For different conditions, theoretical "HRA" and "fm" values are predicted using the mathematical models and results are compared with the experimental values in the following Tables **4-9** for the G1 and G2 materials.

6. RESULTS AND DISCUSSION

Micro structural analysis [12] of Induction hardened Rack components can provide important information regarding material properties, reliability and intensity of surface hardening process. The photo micrographs [13] of the Induction hardened specimens are studied. The surface hardness for the different heat treatment conditions for the materials AISI 1040 AISI 4140, AISI 4340, AISI 1055, AISI 6150 and AISI 9255 are measured and reported in the Table **2**.

From the microstructures of medium carbon steels (Figs. **1-6**) it is evident that there is a considerable conversion of austenite to martensite at the outer surface which improves the hardness in Induction hardened components. It is seen from the Tables **4-9** under optimal conditions that the volume fraction of martensite is almost 95% for both the G1 and G2 materials and also the required hardness (79 – 82 HRA) is obtained.

Because of the temperature dependent non-linear properties in Induction hardening process, analytical solution

Table 4.   Validation of Simulated Results for the AISI 1040 Steel Material

Process Variables			Tq	Theoretical Values		Experimental Values		% Error	
P	S	Q		HRA	fm	HRA	fm		
4.5	1.72	15	-	85.6	1.177	Over hardening	More than one		
5.5	1.72	15	65°C	81	1.006	80	0.96	1.25	4.123
5.8	1.74	15	110°C	79.6	0.95	80	0.95	0.50	0.00
6.0	1.76	15	140°C	78.7	0.9088	79	0.92	0.379	1.217
7	1.72	15		74.105	0.760	Under hardening	Martensite formation is less		

Table 5. Validation of Simulated Results for the AISI 4140 Steel Material

Process Variables			Tq	Theoretical Values		Experimental Values		% Error	
P	S	Q		HRA	fm	HRA	fm		
4.5	1.72	15	-	84.60	11779	Over hardening	More than one	-	
5.5	1.72	15	63°C	80.5	1.006	81.0	0.962	0.617	4.573
5.8	1.74	15	107°C	79.2	0.951	80.0	0.938	1.000	1.385
6.0	1.76	15	140°C	78.4	0.908	79.5	0.910	1.383	0.219
7	1.72	15		74.30	0.7646	Under hardening	Martensite formation is less	-	

Table 6. Validation of Simulated Results for the AISI 4340 Steel Material

Process Variables			Tq	Theoretical Values		Experimental Values		% Error	
P	S	Q		HRA	fm	HRA	fm		
4.5	1.72	15	-	84.0	1.177	Over hardening	More than one	-	
5.5	1.72	15	60°C	80.2	1.01	82	0.967	2.195	4.446
5.8	1.74	15	105°C	79.0	0.95	81	0.930	2.469	2.150
6.0	1.76	15	137°C	78.0	0.90	79	0.90	1.265	0.000
7	1.72	15		74.0	0.760	Under hardening	Martensite formation is less	-	

Table 7. Validation of Simulated Results for the AISI 1055 Steel Material

Process Variables			Tq	Theoretical Values		Experimental Values		% Error	
P	S	Q		HRA	fm	HRA	fm		
4.5	1.72	15	-	85.0	1.21	Over hardening	More than one	-	
5.5	1.72	15	65°C	82.0	1.03	83.0	0.95	1.204	8.420
5.8	1.74	15	110°C	81.0	0.96	81.0	0.92	0.000	4.347
6.0	1.76	15	140°C	80.0	0.92	79.5	0.89	0.628	3.370
7	1.72	15		76.0	0.76	Under hardening	Martensite formation is less	-	

Table 8. Validation of Simulated Results for the AISI 6150 Steel Material

Process Variables			Tq	Theoretical Values		Experimental Values		% Error	
P	S	Q		HRA	fm	HRA	fm		
4.5	1.72	15	-	86.0	1.209	Over hardening	More than one	-	
5.5	1.72	15	47°C	82.0	1.03	81.0	0.96	1.234	7.291
5.8	1.74	15	65°C	81.0	0.96	82.0	0.92	1.219	4.347
6.0	1.76	15	77°C	80.0	0.92	80.0	0.90	0.000	2.222
7	1.72	15		75.5	0.768	Under hardening	Martensite formation is less	-	

Table 9. Validation of Simulated Results for the AISI 9255 Steel Material

Process Variables			Tq	Theoretical Values		Experimental Values		% Error	
P	S	Q		HRA	fm	HRA	fm		
4.5	1.72	15	-	86.0	1.20	Over hardening	More than one	-	
5.5	1.72	15	36°C	82.2	1.03	84	0.94	2.142	9.574
5.8	1.74	15	52°C	81.0	0.96	83	0.92	2.409	4.347
6.0	1.76	15	70°C	80.0	0.92	81	0.92	1.234	0.000
7	1.72	15		76.08	0.76	Under hardening	Martensite formation is less	-	

Fig. (1). Microstructure of Induction hardened AISI 1040.

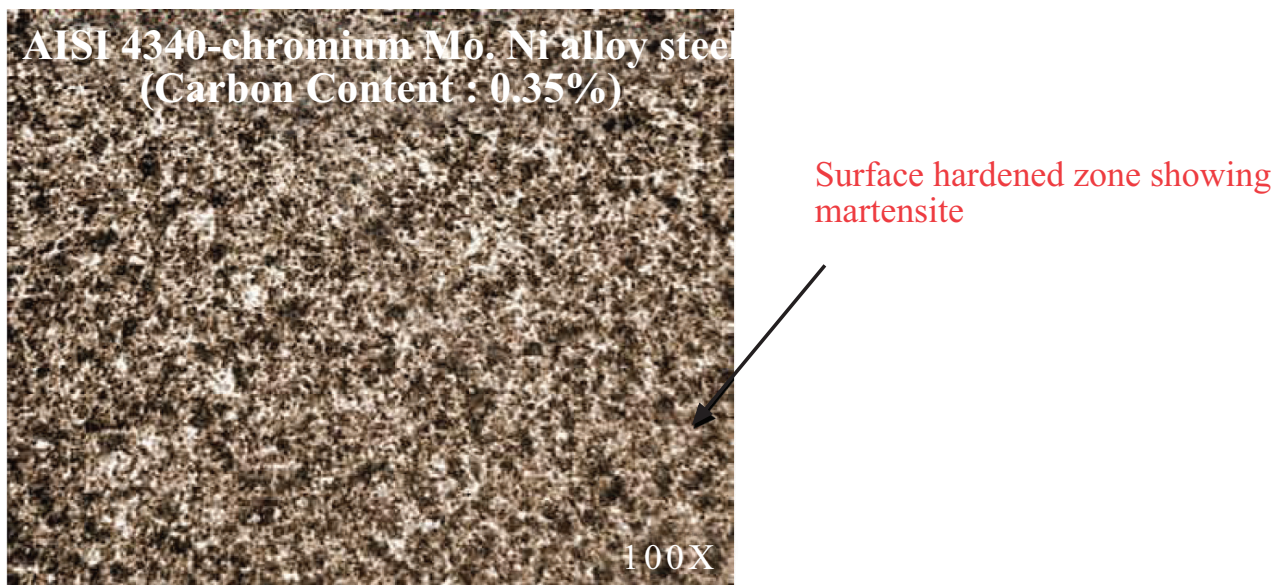**Fig. (2).** Microstructure of Induction hardened AISI 4140.

Fig. (3). Microstructure of Induction hardened AISI 4340.

Surface hardened zone showing
martensite

Fig. (4). Microstructure of Induction hardened AISI 1055.
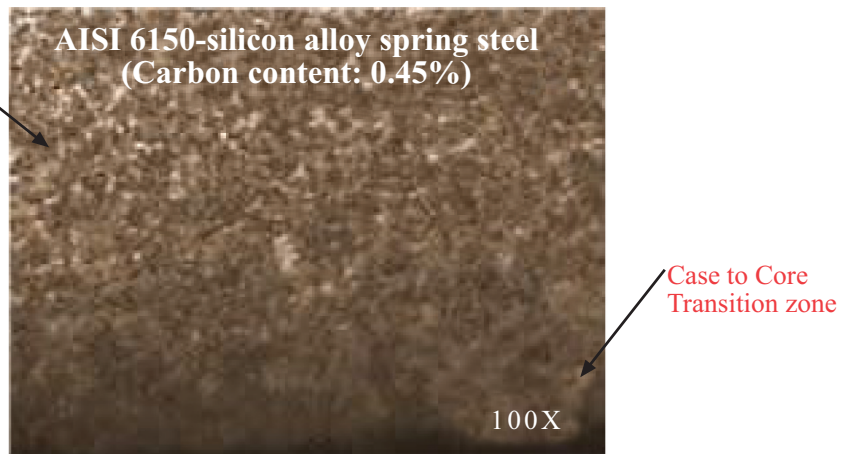
Surface hardened zone showing
martensite

Case to Core
Transition zone

Fig. (5). Microstructure of Induction hardened AISI 6150.

Surface hardened zone showing
martensite

Case to Core
Transition zone

Fig. (6). Microstructure of Induction hardened AISI 9255.

Table 10. Induction Hardening Mathematical Model

S. No.	Materials	Hardness Equations (Hardness in HRA)	Volume Fraction of Martensite (fm)
01	AISI 1040	$Y_H = 107.2820-4.5995P+0.1873S-0.0889Q$	$fm = \{[(HRC)max – 11.96P + 5.27Q]0.0236S^{-1}\}$
02	AISI 4140	$Y_H = 102.33421- 4.0993P+0.4140S+0.0001Q$	
03	AISI 4340	$Y_H = 111.5611-4.1474P-2.3059S-0.2889Q$	$(HRC)max = 60$
04	AISI 1055	$Y_H = 106.7885-3.8179P-3.8671S+0.1778Q$	$fm = \{[(HRC) max – 13.68P + 6.05Q] 0.022S^{-1}\}$
05	AISI 6150	$Y_H = 108.2939-4.1947P-0.2082S-0.2000Q$	
06	AISI 9255	$Y_H = 102.9862-4.0.759P+0.6014S+0.0667Q$	$(HRC)max = 65$

P-Power Potential in kW/inch^2, S-Scan speed in m/min, Q-Quench flow rate in liters/min.

Table 11. Induction Hardening Mathematical Model

S. No.	Materials	Hardness Equations (Hardness in HRA)	Volume Fraction of Martensite (fm)
01	AISI 1040	$Y_H = 108-4.695P+0.4S-0.888Q$	$fm = \{[(HRC)max – 11.96P + 5.27Q]0.0236S^{-1}\}$
02	AISI 4140	$Y_H = 118.68-6.63P+0.32866S-0.0667Q$	
03	AISI 4340	$Y_H =111.66-4.14P-2.358S-0.2884Q$	$(HRC)max = 60$
04	AISI 1055	$Y_H =184.43-3.8175P-46.177S+0.177Q$	$fm = \{[(HRC) max – 13.68P + 6.05Q] 0.022S^{-1}\}$
05	AISI 6150	$Y_H =110.7688-4.167P-0.2776S-0.244Q$	
06	AISI 9255	$Y_H =102.64-4.221P+0.41666S+0.088Q$	$(HRC)max = 65$

where,
P-Power Potential in kW/inch^2.
S-Scan speed in m/min.
Q-Quench flow rate in liters/min.

is very difficult to obtain [14]. When surfaces with complex geometric shape are heat treated the problems become more cumbersome. It must also be remembered that cooling curves are difficult to obtain in Induction hardening applications [15]. Hence, mathematical models will allow engineers/metallurgists to experiment with the critical process variables such as Power potential, Scan speed Quench flow rate and Frequency before expensive investment or unforeseen failures in mass produced items.

A Mathematical Model (details are given in the Table **10**) to predict volume fraction of martensite and hardness in the Induction hardening process has been developed for the Group 1 and Group 2 materials.

Comparisons between the theoretically simulated and experimental results are shown in the Tables **4-9**. It can be observed that there is a good agreement between the two results. The difference between the results (error) may be attributed to the lack of precision in measurement of Tq. It can also be seen that there is a reduction in the starting temperature of Martensite formation (Table **3**) when the carbon percentage increases from 0.35 – 0.55. However, the addition of alloying elements improves the properties like wear resistance, corrosive resistance, ductility etc. but decreases the hardness.

7. CONCLUDING REMARKS

- Microstructural analysis indicates that there is a moderate conversion of austenite to martensite (Phase Transformations) at the outer surface which improves the Hardness in Induction hardened components.

- A Mathematical Model (details are given in the Table **11**) to predict volume fraction of martensite and hardness in the induction hardening process has been developed. It is shown that the numerical predictions of the hardened layer are in good agreement with the experimental results.

ACKNOWLEDGEMENTS

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