Residual Stresses in Case Hardened Materials

K. Palaniradja*, N. Alagumurthi and V. Soundararajan

Department of Mechanical Engineering, Pondicherry Engineering College, Pondicherry – 605 014, India

Abstract: Fatigue behavior of case hardened parts depend to a great extent on the type of residual stresses developed in the components. Topography and metallurgical effects were the two elements which contribute much to surface integrity. Micro hardness of the gas carburized (EN 33 and EN 36) and Induction hardened (AISI 1040 and AISI 6150) specimens obtained during experiments, showed that there was gradual decrease of hardness from surface to sub-surface. Results also showed that more the hardness and case depth, the more was the residual stress. The optimum results gave the maximum compressive residual stress in both the gas carburizing and Induction hardening process irrespective of the mechanisms involved in the process. The X-ray diffraction test showed that the distribution of residual stress was uniform both on the surface and beneath the surface. The magnitude and distribution of residual stress obtained from the experiment agreed with the FEM results found in literatures.

Keywords: Residual stress, case hardening, tensile stress, compressive stress, micro hardness.

1. INTRODUCTION

In many applications, like Automobiles, heavy duty machines, et., where the machine elements are subjected fatigue loading, Gas carburized and Induction hardened components are used. Fatigue behaviour of case hardened parts depends to a great extent on the type of residual stress developed in the components. In Gas Carburizing and Induction hardening the heating and sudden cooling causes phase transformations on the surface layer and beneath the surface of the workpiece. Heat treatment temperature, Quenching Temperature, Type of Quenchant, Quenching period, heat treatment period are major variables, which influence the phase transformation [1].

Phase transformation affects the surface layer characteristics/surface integrity. The concept of surface integrity cannot be defined one dimensionally and does not only embrace the surface hardness, surface roughness, case depth or its geometrical shape, but also the characteristics of the surface and the layers directly underneath it. It comprehends the mechanical, physical-chemical, metallurgical and technological properties. Surface integrity is defined as the unimpaired surface conditions, which are developed in hardware by using controlled heat treatment operations [2]. Two elements comprise the surface integrity. The first is the topography and the second is the metallurgical alternations produced at or near the surface. It thus includes dimensional accuracy, residual stresses and metallurgical damage of the heat treated component.

Surface integrity assumes importance for the reasons listed below:

- ❖ Higher stress levels to which the materials are subjected
- ❖ Reliability demands are stringent
- ❖ Components with critical sections are becoming more in use

The surface integrity of any part produced depends on

- ❖ The state of material before the heat treatment starts.
- ❖ The processing variable
- ❖ The energy levels during the case hardening process and
- ❖ The type of quenchant and rate of quenching

Of all the properties that describe the surface layer characteristics residual stresses regarded as the most representative one as far as mechanical applications are concerned,. In heat treated components, residual stresses developed are due to phase transformation and non-uniform deformation during heating and cooling cycles [3]. In case of phase transformation, if the transformation is martensite to ferrite or pearlite the volume decreases hindered by the bulk material produces tensile residual stresses. If the phase transformation is ferrite to pearlite to martensite the volume increases hindered by the bulk material produces compressive residual stresses. These stresses influence the mechanical properties like fatigue strength depending on their nature, magnitude and distribution across the body. There is basically no material or situation free of this stresses. Hence, the general interest is the recognition and measurement of these residual stresses [4].

With the recent improvement on machines to measure the residual stress through XRD, the interest on the knowledge to control such stresses has increased. This interest has its importance due to the fact that the presence of the residual stress interferes with the fatigue strength of the Materials [5].

*Address correspondence to this author at the Department of Mechanical Engineering, Pondicherry Engineering College, Pondicherry-605014, India; Tel: 91 413 2655281-287, Ext. 252,259; Fax: 91 413 2655101;
E-mail: palaniradja72@rediffmail.com

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2. RESIDUAL STRESS IN GAS CARBURIZING

The development of residual stresses, final microstructure and mechanical properties in the case and core of the carburized components depends on complex interactions among steels composition, component size and geometry, carburizing and subsequent austenitizing process parameters., heat transfer associated during quenching and time and temperature parameters of tempering.

Component geometry (size and shape) together with heat transfer associated with quenching conditions (i.e., cooling performance of the quenchant, agitation etc.,) affect the final residual stress state developed in casehardened steels as a result of quenching. Carburized microstructure is almost always tempered to transform the unstable and brittle martensite into stable tempered martensite [6, 7]. Tempering decreases residual stresses and this is promoted by increasing the tempering temperature.

With this in mind an experimental investigation is performed using EN33 (AISI 3310) and EN36 (AISI 8620) steel material to study the surface integrity issue with main focus on Residual stress in Gas Carburizing Process.

The Fig. (**1**) shows the measurement of residual stress in the gas carburized components. On the helix (a), groove (b), knurled region(c) and cylindrical surface (d) of the pinion material residual stresses are measured using residual stress analyzer by X-ray diffraction technique and the average surface residual stress is taken for the analysis [8]. The residual stress beneath the top surface is measured upto a maximum depth of 1mm in the intervals of 0.1mm.

Table **1** gives the details on the materials [9, 10] subjected for Gas Carburizing (Residual stress analysis). Table **2** shows the operating parameters and their levels adopted in Gas Carburising process. Table **3** gives the experimental design matrix and Table **4**, shows the test results.

The experiments have been conducted based on L27 orthogonal array system proposed in Taguchis' Mixed level series DOE with interactions as given below:

i) Furnace Temperature *vs* Quenching Time (AxB)

ii) Furnace Temperature *vs* Tempering Temperature (AxC)

3. RESIDUAL STRESS IN INDUCTION HARDENING

In Induction hardening, the components are heated usually for a few seconds only. The hardening temperature varies from 760 – 800ºC. The major influencing variables in Induction Hardening are the Power potential, Scan speed and Quench flow rate. The process variables are having a definite relation with hardness and volume fraction of martensite of the hardened components [11]. The attainment of correct combination of surface hardness, hardness penetration depth

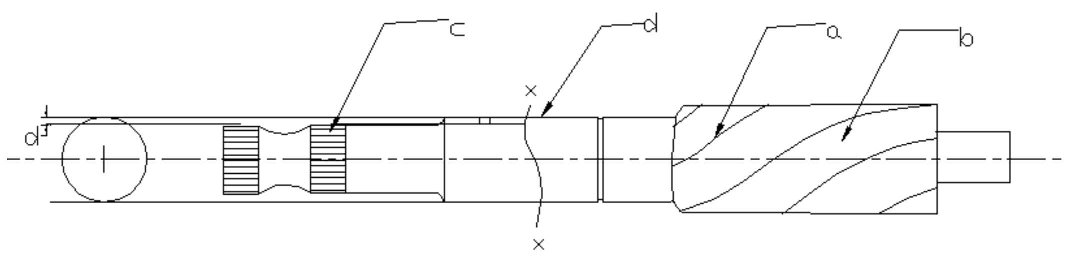


Fig. (1). Residual stress measurement locations on the Gas carburized component.

Table 1. Materials Used in Gas Carburizing

S. No.	Type	Designation	Chemical Composition in Percentage	Size
01	Nickel alloy steel	EN 33	C-0.15%, Si-0.35%, Mn-0.60%, Cr-0.30%, Ni-3.5%, S&P each -0.05%	Diameter = 17.3 mm Length = 150 mm
02	Chromium alloy steel	EN 36	C-0.18%, Si-0.10%, Mn-0.30%, Cr-0.60%, Ni-3.0% S&P each – 0.05&	

Table 2. Gas Carburizing-Operating Conditions

S. No.	Variables	Notation	Level 1	Level 2	Level 3
1	Furnace temperature	A	870°C	910°C	940°C
2	Quenching Time	B	60 minutes	90 minutes	120 minutes
3	Tempering Temperature	C	150°C	200°C	250°C
4	Tempering Time	D	80 minutes	100 minutes	120 minutes
5	Preheating	E	No Preheating	150°C	No Preheating

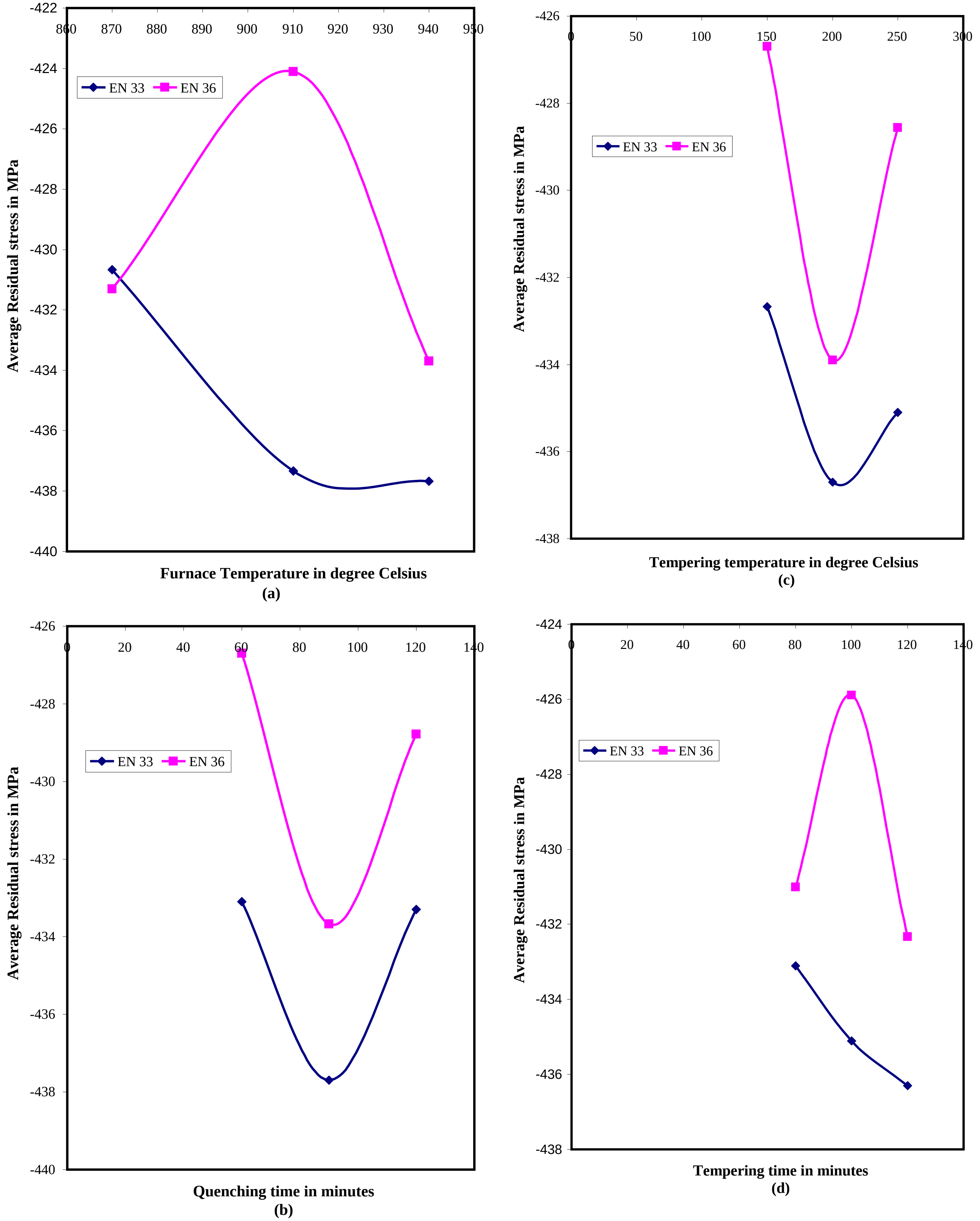
Table 3. Experimental Design Matrix

TRIAL	A	B	AXB	AXB	C	AXC	AXC	D	E
1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2
5	1	2	2	2	2	2	2	3	3
6	1	2	2	2	3	3	3	1	1
7	1	3	3	3	1	1	1	3	3
8	1	3	3	3	2	2	2	1	1
9	1	3	3	3	3	3	3	2	2
10	2	1	2	3	1	2	3	1	2
11	2	1	2	3	2	3	1	2	3
12	2	1	2	3	3	1	2	3	1
13	2	2	3	1	1	2	3	2	3
14	2	2	3	1	2	3	1	3	1
15	2	2	3	1	3	1	2	1	2
16	2	3	1	2	1	2	3	3	1
17	2	3	1	2	2	3	1	1	2
18	2	3	1	2	3	1	2	2	3
19	3	1	3	2	1	3	2	1	3
20	3	1	3	2	2	1	3	2	1
21	3	1	3	2	3	2	1	3	2
22	3	2	1	3	1	3	2	2	1
23	3	2	1	3	2	1	3	3	2
24	3	2	1	3	3	2	1	1	3
25	3	3	2	1	1	3	2	3	2
26	3	3	2	1	2	1	3	1	3
27	3	3	2	1	3	2	1	2	1

Table 4. Gas Carburizing Test Results Materials: EN 33 and EN 36

S. No.	Hardness in HRA		Case Depth in mm		Residual Stress in MPa	
	EN 33	EN 36	EN 33	EN 36	EN 33	EN 36
01	78.0	76.0	0.75	0.75	-425	-423
02	78.5	78.0	0.80	0.75	-430	-423
03	79.0	77.0	0.75	0.80	-428	-430
04	79.0	77.5	0.80	0.85	-432	-432
05	81.0	78.5	0.75	0.85	-442	-436
06	81.0	80.0	0.75	0.80	-438	-450
07	81.0	80.0	0.65	0.70	-430	-434
08	78.0	80.5	0.70	0.70	-423	-432
09	79.0	76.0	0.70	0.70	-428	-422
10	79.0	77.0	0.75	0.70	-428	-424
11	79.0	77.0	0.85	0.85	-438	-426
12	79.5	78.0	0.85	0.80	-440	-427
13	79.5	78.0	0.85	0.80	-438	-426
14	78.0	77.0	0.90	0.75	-440	-424
15	78.5	78.5	0.80	0.75	-442	-422
16	80.0	78.5	0.75	0.70	-440	-420
17	81.0	78.5	0.75	0.85	-438	-427
18	77.0	76.0	0.85	0.85	-432	-421
19	78.0	77.5	0.85	0.75	-436	-427
20	80.5	80.0	0.85	0.70	-442	-432
21	79.0	79.5	0.70	0.80	-431	-429
22	78.5	76.5	0.80	0.85	-433	-424
23	81.5	81.5	0.80	1.00	-448	-460
24	79.0	78.0	0.95	0.90	-434	-429
25	80.0	78.5	0.80	0.90	-438	-431
26	79.5	80.0	0.80	0.95	-434	-445
27	80.0	77.0	0.90	0.90	-446	-427

(Fig. 2) contd…..


EN 33
EN 36
Average Residual stress in MPa
-422
-424
-426
-428
-430
-432
-434
-436
-438
-440
860 870 880 890 900 910 920 930 940 950
Furnace Temperature in degree Celsius
(a)
0 50 100 150 200 250 300
Tempering temperature in degree Celsius
(c)
0 20 40 60 80 100 120 140
Quenching time in minutes
(b)
Tempering time in minutes
(d)

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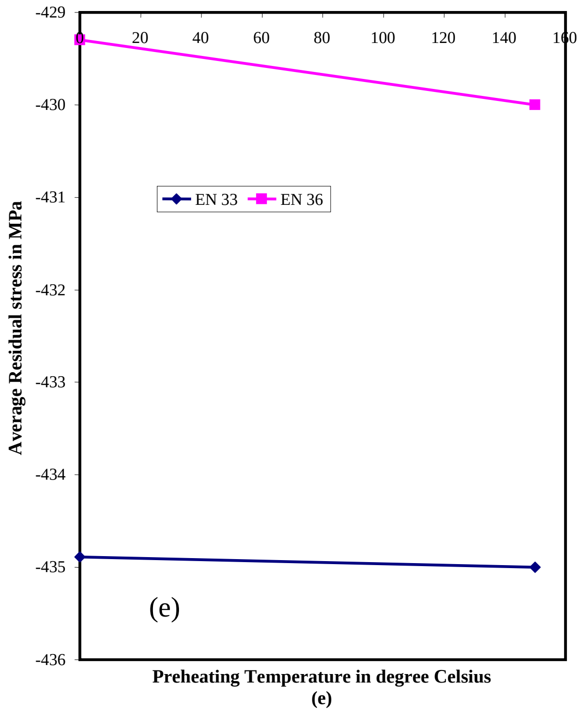


Fig. (2). **(a-e)** Process variables *vs* residual stress.

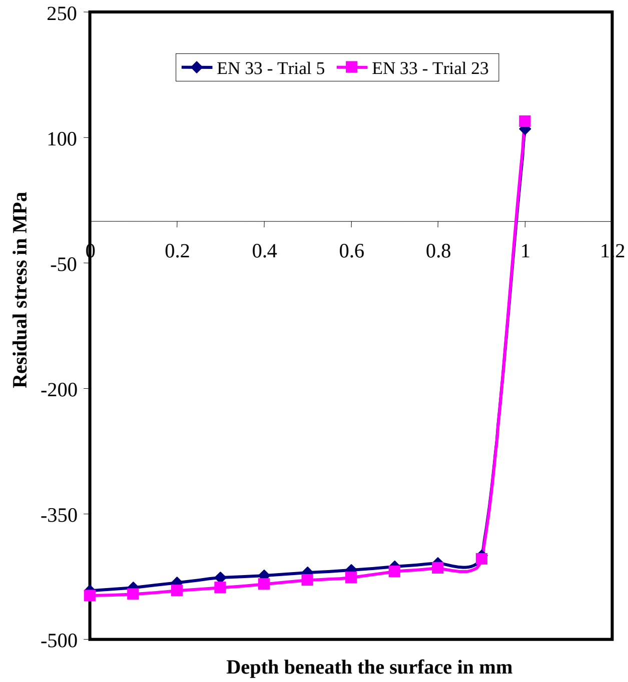


Fig. (3). Depth beneath the surface *vs* Residual stress (EN 33 - Gas Carburizing Process).

Table 5. Residual Stress and Micro Hardness Values of the Gas Carburized Component for the Selected set of Trials Material: EN 33

Depth Beneath the Surface in mm	Micro Hardness in VHN		Residual Stress in MPa	
	Trial 5	Trial 23	Trial 5	Trial 23
Surface	610	620	-442	-448
0.1	600	614	-438	-446
0.2	595	600	-432	-442
0.3	590	594	-426	-438
0.4	585	590	-424	-434
0.5	584	587	-420	-429
0.6	582	584	-417	-426
0.7	579	576	-413	-419
0.8	572	564	-409	-415
0.9	564	561	-400	-404
1.0	550	550	+110	+119

Table 6. Residual Stress and Micro Hardness Values of the Gas Carburized Component for the Selected Set of Trials Material: EN 36

Depth Beneath the Surface in mm	Micro Hardness in VHN		Residual Stress in MPa	
	Trial 6	Trial 26	Trial 6	Trial 26
surface	618	600	-450	-445
0.1	615	596	-446	-442
0.2	612	593	-442	-436
0.3	606	589	-437	-432
0.4	598	584	-434	-428
0.5	589	578	-429	-424
0.6	577	574	-424	-419
0.7	569	568	-419	-414
0.8	562	562	-411	-407
0.9	554	558	-401	-400
1.0	550	552	+115	+112

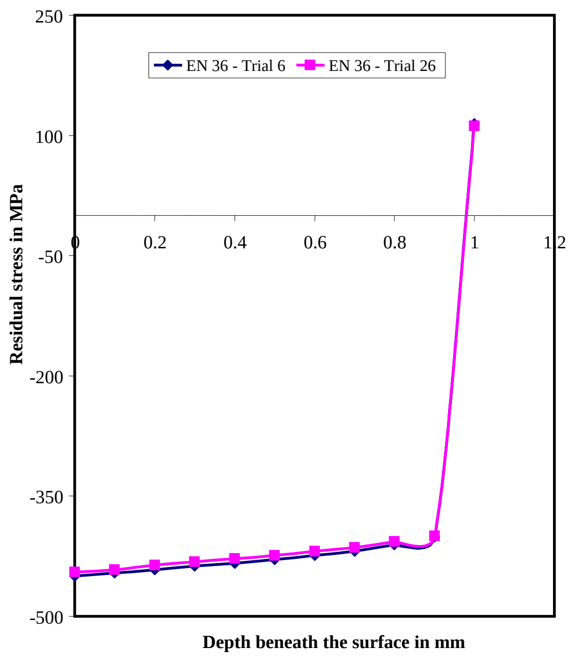


Fig. (4). Depth beneath the surface *vs* Residual stress (EN 36 - Gas Carburizing Process).

and high magnitude of compressive residual stress with permitted level of distortion requires the use of proper and optimized process variables.

The surface residual stress and the sub-surface residual stress are of great importance on the fatigue resistance of the materials [12]. Number of researchers report that if those stresses are of compressive natures improve the resistance to fatigue whereas if those stresses are of tensile nature depending on their magnitude they contribute to a decline in the fatigue resistance [13]. In order to verify the behaviour of the residual stress in the surface and sub-surface of the Induction hardened components, experiments have been conducted.

The Fig. (**5**) shows the details on the measurement of residual stress in the Induction hardened components. The measurement was taken at three places, namely teeth (a), groove (b) and cylindrical surface (c). Residual stresses are measured using residual stress analyzer by X-ray diffraction technique and the average surface residual stress is taken for the analysis [14]. The residual stress beneath the top surface is measured upto a maximum depth of 1mm in the intervals of 0.1mm.

Table **7** gives the details on the materials subjected for Induction Hardening (Residual stress analysis). Table **8** shows the operating variables and their levels adopted in

Table 7. Materials Used for Induction Hardening (Residual Stress Analysis)

S. No.	Type	Designation	Chemical Composition in Percentage	Size
01	Unalloyed carbon steel	AISI 1040	C-0.35%, Si-0.10%, Mn-0.60% S&P each 0.06%	Diameter = 23 mm Length = 200 mm
02	Silicon alloy steel	AISI 6150	C-0.50%, Si–0.50%, Mn-0.50%, Cr-0.80%, V-0.15% S&P each -0.05(each)	

Table 8. Induction Hardening Operating Conditions

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

Table 9. Experimental Design Matrix

S. No.	Factors and Treatment			S. No.	Factors and Treatment			S. No.	Factors and Treatment		
	P	S	Q		P	S	Q		P	S	Q
1	L1	L1	L1	10	L2	L1	L1	19	L3	L1	L1
2	L1	L1	L2	11	L2	L1	L2	20	L3	L1	L2
3	L1	L1	L3	12	L2	L1	L3	21	L3	L1	L3
4	L1	L2	L1	13	L2	L2	L1	22	L3	L2	L1
5	L1	L2	L2	14	L2	L2	L2	23	L3	L2	L2
6	L1	L2	L3	15	L2	L2	L3	24	L3	L2	L3
7	L1	L3	L1	16	L2	L3	L1	25	L3	L3	L1
8	L1	L3	L2	17	L2	L3	L2	26	L3	L3	L2
9	L1	L3	L3	18	L2	L3	L3	27	L3	L3	L3

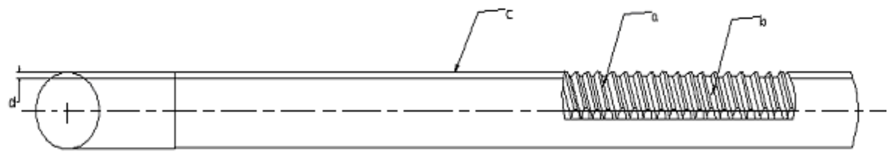


Fig. (5). Residual stress measurement locations on the Induction hardened component.

Induction hardening process. Table **9** shows the Experimental design matrix. Tables **10-12** show the test results.

The experiments have been conducted based on 3^3 full factorial DOE.

4. RESULTS AND DISCUSSION

Micro hardness of the Gas carburized (EN 33 and EN 36) and Induction hardened (AISI 1040 and AISI 6150) specimens are found by using Vickers microhardness tester and reported in the Tables **5**, **6**, **12** and **13**. The higher hardness resulted from the outer surface is due to the formation of martensite, which is obtained during the diffusion, and phase transformation of surface layers with self-quenching. Micro hardness analysis gives that there is a gradual decrease of hardness from surface to sub-surface.

The surface hardness in HRA, case depth in mm, Residual stress in MPa for different experimental combinations of Gas carburized specimens are shown in Table **4**. Study indicates that more the hardness and case

Table 10. Induction Hardening Test Results Material: AISI 1040

S. No.	Factors and Treatment			Hardness in HRA	Distortion in mm	Case Depth Below the Teeth in mm	Case Depth Back of the Bar in mm	Residual Stress in MPa
	P	S	Q					
1	L1	L1	L1	80.0	2.00	2.00	4.10	-746
2	L1	L1	L2	78.0	2.15	2.20	3.80	-736
3	L1	L1	L3	79.0	1.90	1.85	3.20	-742
4	L1	L2	L1	78.0	0.80	2.50	1.20	-747
5	L1	L2	L2	80.0	1.60	1.80	2.70	-746
6	L1	L2	L3	82.0	2.10	2.20	4.20	-750
7	L1	L3	L1	83.0	2.40	2.30	2.30	-744
8	L1	L3	L2	74.0	1.30	1.80	2.90	-734
9	L1	L3	L3	81.0	1.50	1.50	3.70	-744
10	L2	L1	L1	74.0	2.40	2.60	2.90	-727
11	L2	L1	L2	78.0	2.60	2.40	2.60	-738
12	L2	L1	L3	77.0	1.70	1.90	1.90	-734
13	L2	L2	L1	78.0	2.00	1.90	3.10	-737
14	L2	L2	L2	74.0	2.40	2.50	2.30	-727
15	L2	L2	L3	76.0	2.30	2.30	3.30	-732
16	L2	L3	L1	78.0	1.30	1.35	2.60	-741
17	L2	L3	L2	74.0	1.20	1.40	2.90	-726
18	L2	L3	L3	78.0	2.10	2.00	1.80	-734
19	L3	L1	L1	69.0	1.00	1.30	1.70	-724
20	L3	L1	L2	65.0	1.25	1.65	2.10	-721
21	L3	L1	L3	67.0	0.95	1.30	1.10	-723
22	L3	L2	L1	64.0	0.70	1.40	1.30	-723
23	L3	L2	L2	62.0	0.85	1.30	0.95	-720
24	L3	L2	L3	63.0	0.80	1.35	1.40	-722
25	L3	L3	L1	68.0	0.95	1.30	1.00	-728
26	L3	L3	L2	67.0	1.10	1.50	1.40	-724
27	L3	L3	L3	65.0	1.20	1.40	1.10	-722

Table 11. Induction Hardening Test Results Materials: AISI 6150

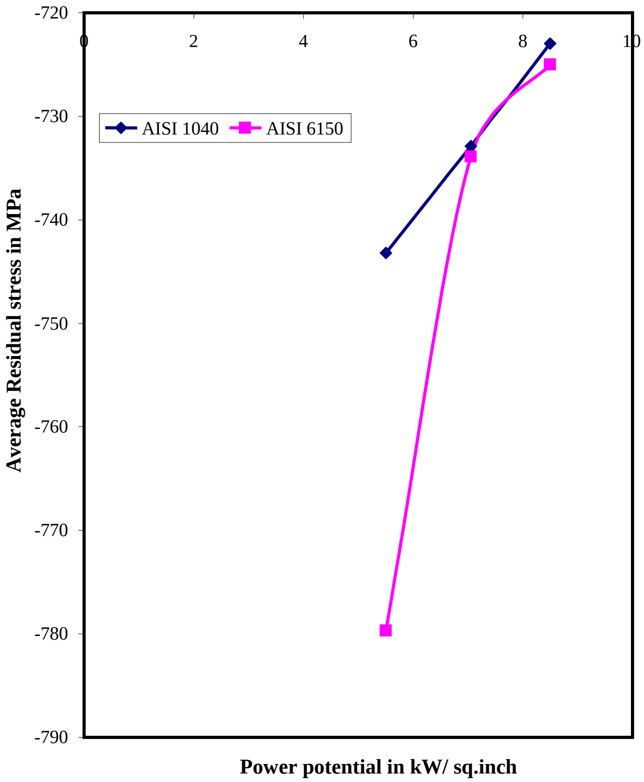
S. No.	Factors and Treatment			Hardness in HRA	Distortion in mm	Case Depth Below the Teeth in mm	Case Depth Back of the Bar in mm	Residual Stress in MPa
	P	S	Q					
1	L1	L1	L1	83.0	2.40	2.20	4.20	-804
2	L1	L1	L2	82.0	2.20	2.10	3.90	-800
3	L1	L1	L3	80.0	2.00	2.00	4.20	-794
4	L1	L2	L1	80.0	2.10	1.90	3.50	-736
5	L1	L2	L2	84.0	0.80	1.80	3.10	-738
6	L1	L2	L3	79.0	2.30	2.20	3.00	-744
7	L1	L3	L1	80.0	1.90	2.10	3.40	-796
8	L1	L3	L2	84.0	2.00	1.10	2.90	-800
9	L1	L3	L3	84.0	2.00	1.80	4.10	-805
10	L2	L1	L1	78.0	1.60	2.70	3.20	-732
11	L2	L1	L2	70.0	1.70	1.70	3.20	724
12	L2	L1	L3	73.0	1.80	1.90	3.60	-738
13	L2	L2	L1	70.0	1.25	1.60	3.40	-741
14	L2	L2	L2	76.0	2.50	1.80	3.80	-732
15	L2	L2	L3	77.0	1.60	1.30	2.10	-741
16	L2	L3	L1	73.0	1.70	1.80	2.80	-729
17	L2	L3	L2	75.0	1.30	1.70	3.70	-736
18	L2	L3	L3	74.0	1.00	1.70	3.00	-732
19	L3	L1	L1	78.0	1.30	1.40	1.80	-724
20	L3	L1	L2	70.0	0.70	1.30	1.70	-727
21	L3	L1	L3	67.0	1.30	1.30	1.50	-723
22	L3	L2	L1	68.0	1.50	1.70	0.90	-728
23	L3	L2	L2	64.0	0.90	1.60	1.40	-724
24	L3	L2	L3	67.0	0.80	1.30	1.60	-731
25	L3	L3	L1	70.0	1.10	1.40	0.90	-724
26	L3	L3	L2	69.0	0.90	1.50	1.00	-721
27	L3	L3	L3	70.0	1.25	1.30	1.20	-723

Table 12. Residual Stress and Micro Hardness Values of the Induction Hardened Component for the Selected Set of Trials Material: AISI 1040

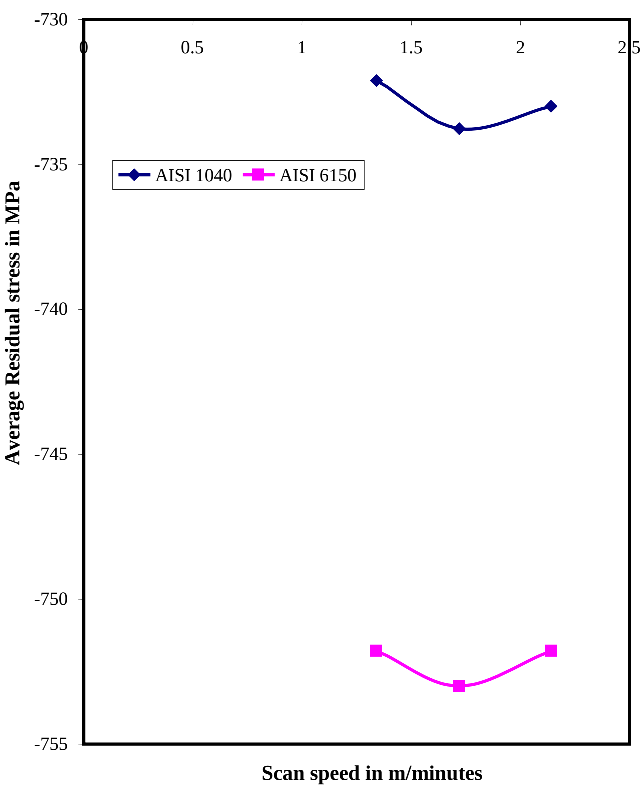
Depth Beneath the Surface in mm	Micro Hardness in VHN		Residual Stress in MPa	
	Trial 6	Trial 16	Trial 6	Trial 16
surface	655	649	-750	-741
0.1	644	636	-747	-738
0.2	636	627	-742	-734
0.3	625	624	-741	-731
0.4	618	615	-736	-728
0.5	612	609	-731	-724
0.6	608	605	-725	-719
0.7	604	598	-720	-714
0.8	594	587	-719	-708
0.9	591	583	-715	-702
1.0	582	574	+210	+227

depth more will be the residual stress formed. The residual stresses formed are compressive in nature and so it may improve the fatigue strength of the material [15].

The surface hardness in HRA, Distortion in mm, Case depth below the teeth of the Rack in mm, Case depth back of the Rack in mm and Residual stress in MPa for different experimental combinations of Induction hardened specimens are shown in Tables **10** and **11**.

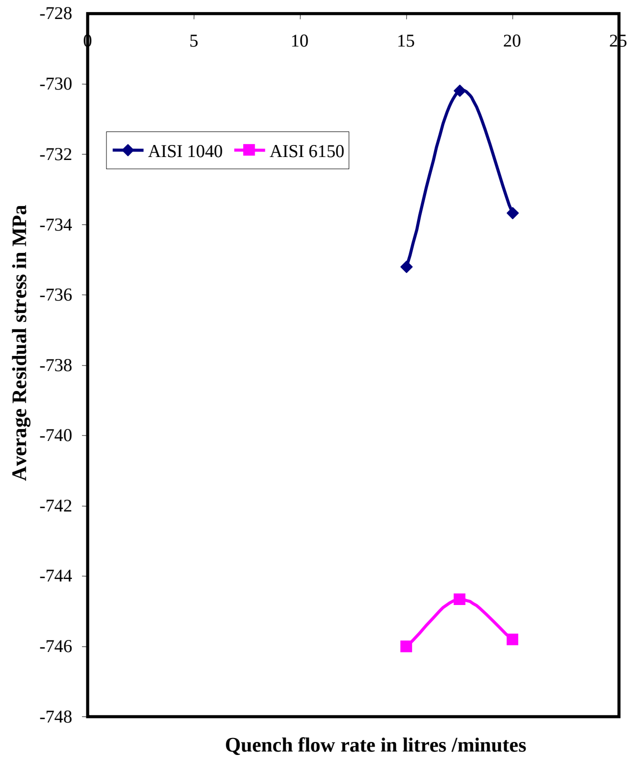


(a)



(b)

(Fig. 6) contd…..



(c)

Fig. (6). (a-c) Process variables *vs* residual stress.

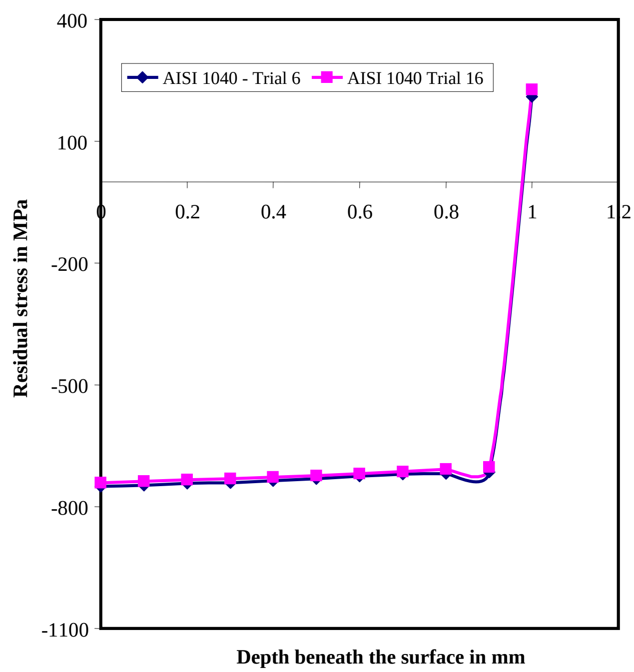


Fig. (7). Depth beneath the surface *vs* residual stress (AISI 1040 steel material - induction hardening process).

Table 13. Residual Stress and Micro Hardness Values of the Induction Hardened Component for the Selected Set of Trials Material: AISI 6150

Depth Beneath the Surface in mm	Micro Hardness in VHN		Residual Stress in MPa	
	Trial 7	Trial 19	Trial 7	Trial 19
surface	670	657	-796	-724
0.1	664	652	-792	-721
0.2	652	649	-787	-716
0.3	640	637	-774	-711
0.4	632	628	-752	-705
0.5	628	624	-743	-698
0.6	620	617	-739	-674
0.7	610	604	-726	-668
0.8	601	597	-719	-657
0.9	596	584	-704	-643
1.0	590	567	+190	+210

The magnitude and the nature of the residual stresses left after heat treatment at different operating conditions have been measured by the X-ray diffraction techniques using the Residual stress analyzer. Residual stress analysis indicates that Induction hardening can give a compressive residual stress of (-) 800MPa for the Low alloyed Medium carbon steels [16]. However, Gas carburising can give a compressive residual stress of (-) 400MPa for Low alloyed Low carbon steels [17].

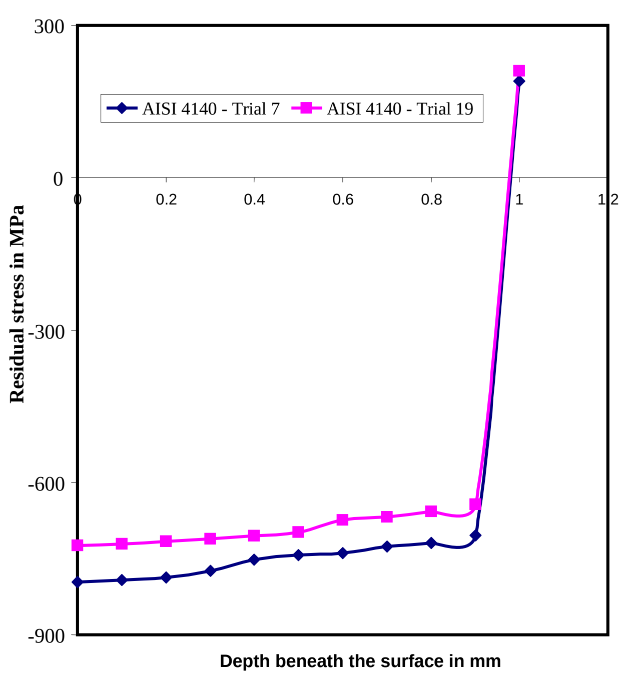


Fig. (8). Depth beneath the surface *vs* residual stress (AISI 4140 steel material - induction hardening process).

It is inferred from the graphs (Figs. (**2a-e**, **6a-c**) that the optimum results gives the maximum compressive residual stress in both the Gas carburizing and Induction hardening process irrespective of the mechanisms involved in the process. Figs. (**3**, **4**, **7**, **8**) shows the Residual stress beneath the surface of the pinion and Rack materials respectively. The X-ray diffraction test shows that the distribution of residual stress is uniform both on the surface and beneath the surface. ***The magnitude and distribution of residual stress obtained from the experimental work agrees with the FEM results given by Dong-hui Xu and Zhen-Bhang Kuang (1996)*** **[18].**

5. CONCLUDING REMARKS

- Micro hardness analysis shows that there is a gradual decrease of hardness from surface to sub-surface.
- Study indicates that more the hardness and case depth more will be the residual stress formed. The residual stresses formed are compressive in nature and it improves the fatigue strength of the material.
- Residual stress analysis indicates that Induction hardening can give a compressive residual stress of (-) 800MPa for the Low alloyed Medium carbon steels. However, Gas carburising can give a compressive residual stress of (-) 400MPa for Low alloyed Low carbon steels.
- The X-ray diffraction test shows that the distribution of residual stress is uniform both on the surface and beneath the surface. ***The magnitude and distribution of residual stress obtained from the experimental work agrees with the FEM results given by Dong-hui Xu and Zhen-Bhang Kuang (1996)*** **[19].**

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