CHAPTER 5

EXPERIMENTAL RESULTS

From the experimental procedure, all results were as followings:

5.1 Material composition results

From the method of ASTM E 415 – 95 for testing the composition of the specimen, the results of chemical composition was shown in the table 5.1.

Table 5.1 The chemical composition of specimen

C	Mn	P	Mo	S	Cr
0.49	0.82	0.013	0.011	0.009	0.169

5.2 Hardness testing results

From the problem analysis, there were two ways to improve the hardness in depth which were:

1. Varying current, whilst the down speed was kept constant.
2. Varying down speed, while the current was kept constant.

5.2.1 The influence of coil current

The results of varying current while the down speed was fixed, were shown in table 6A in Appendix and the average values of each condition shown in Table 5.1, below. From the result in Table 5.1, Figure 5.1 was the curve of hardness distribution from varying current in each observation from surface hardening layer to inner core.

From the result in Figure 5.1, the depth of hardening that case depth was defined with a hardness value of HV 450 as a criterion, could be drawn with the current as shown in Table 5.3 and Figure 5.2. From the depth of hardening, Figure 5.2 illustrated the relation of case depth and coil current at down speed 1.8 mm/sec. for the hardness value of 300, 450, and 600 HV as criterion. If the current was increased while down speed was constant, the depth of hardening will increased, shown in Figure 5.2.

Table 5.1. Mean value of surface hardness and hardness distribution at each depth by the down speed fixed at 1.8 mm/sec.

Current (Amp)		95	100	105	110	115	120	125
Surface Hardness (HRC)		57.7	58.2	59	59.8	60.7	61.7	62.3
Hardness in HV at distance (mm.) from surface	0.1	651	664	680	685	697	698	699
	0.2	647	662	667	667	685	695	684
	0.3	634	641	642	656	669	673	679
	0.4	617	641	640	635	628	662	653
	0.5	586	621	621	621	623	628	632
	0.6	454	563	589	588	610	612	614
	0.7	332	422	438	451	522	557	558
	0.8	265	329	346	416	446	461	478
	0.9	248	277	286	355	369	370	374
	1	238	257	255	258	252	330	332
	1.1	236	238	241	240	247	249	241
	1.2	237	236	238	235	236	235	237
	1.3	236	236	233	235	236	236	238
	1.4	235	238	234	238	237	238	237
	1.5	238	237	233	234	235	236	236
	1.6	237	237	234	235	237	239	235

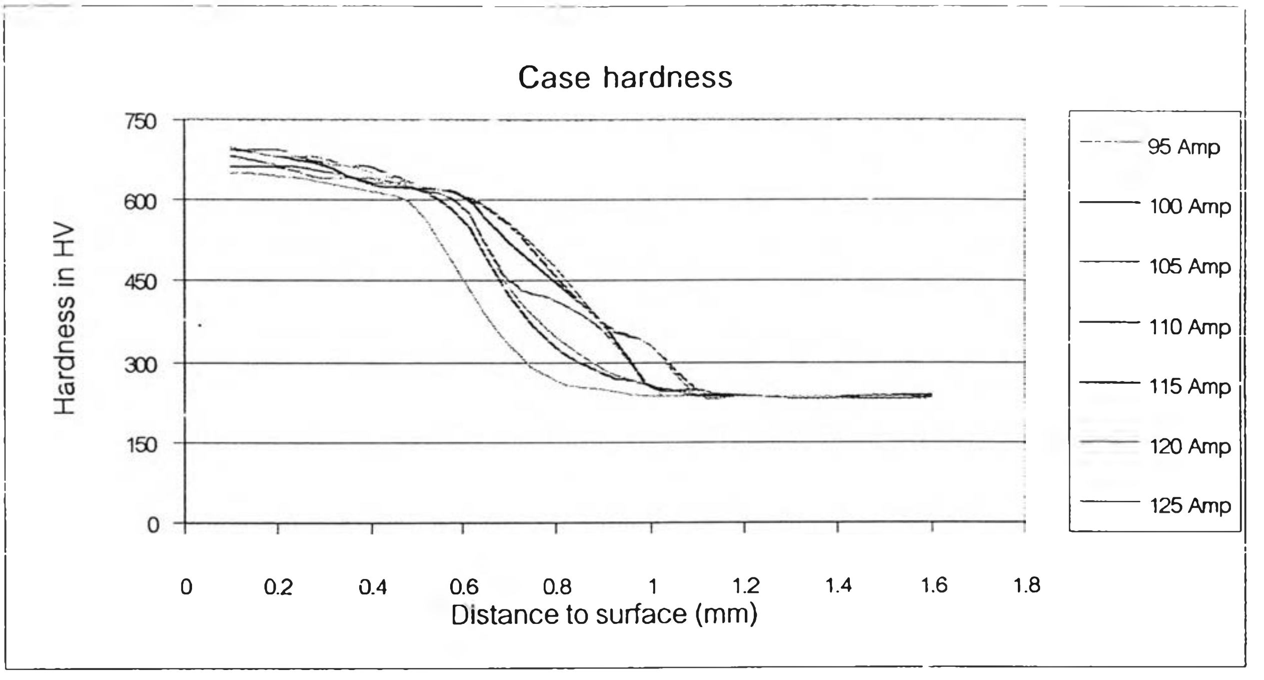

Figure 5.1 Hardness distribution of each current varied

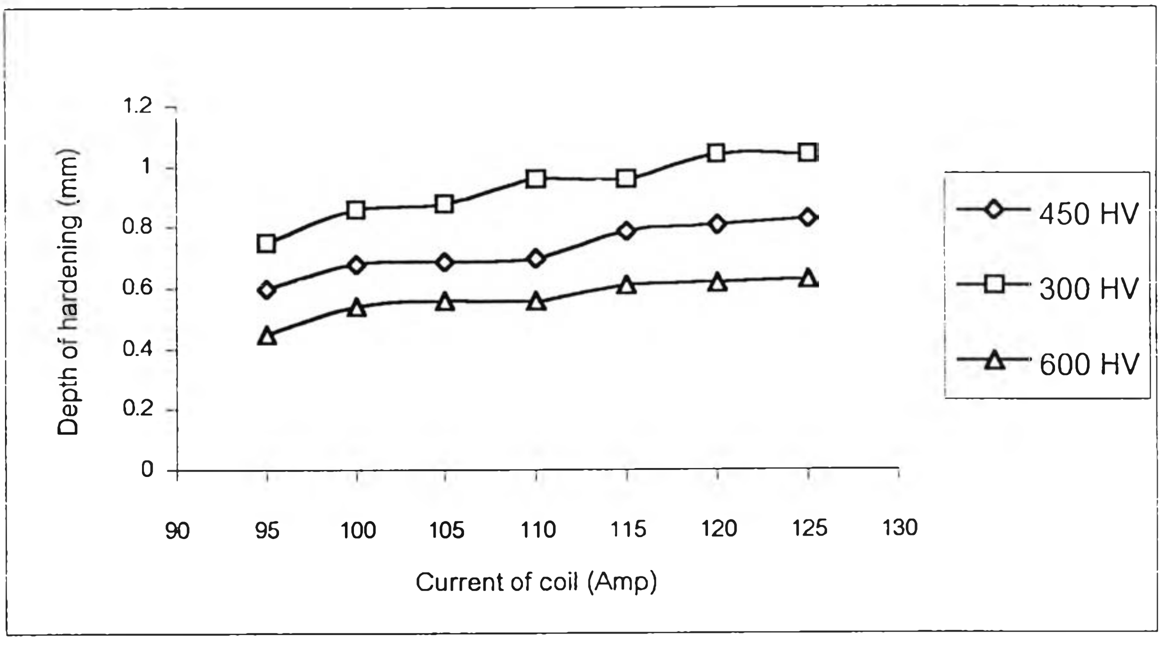

Figure 5.2. The relation of case depth and coil current at down speed 1.8 mm/sec.

Table 5.3 Current and depth of hardening with hardness of 300, 450 and 600 HV

Current	Depth of hardening (mm.)		
(Amp)	300 HV	450 HV	600 HV
95	0.75	0.60	0.45
100	0.86	0.68	0.54
105	0.88	0.69	0.56
110	0.96	0.70	0.56
115	0.96	0.79	0.61
120	1.04	0.81	0.62
125	1.04	0.83	0.63

5.2.2 The influence of down speed

The detailed results from varying down speed when the current was kept constant, were shown in table 6B in Appendix. The average values from each observation were illustrated in Table 5.2, below. From the result in Table 5.4, Figure 5.3 shows the curve of hardness distribution from varying down speed in each observation from surface hardening layer to inner core.

From the result in Figure 5.3, the depth of hardening that case depth was defined with a hardness value of HV 450 as criterion could be drawn with the current as shown in Table 5.5 and Figure 5.4. From the depth of hardening, Figure 5.4 illustrated the relation of case depth and down speed at the current of 105 Amp. for the hardness value of 300, 450, and 600 HV as criterion. From Figure 5.4, the result showed that increasing the down speed the depth of hardening was decreased.

From the data in Table 5.4, it showed that at down speed 1.6 mm./sec, the result had the surface hardness of 58.83 HRC and the hardness of 486 HV at 0.8 mm, shown in Figure 5.5. Nonetheless, if this condition is used in the process, the productivity is lower than before improvement. So the higher down speed were considered to find out the suitable condition giving the higher productivity than this condition, 105 Amp and 1.6 mm/sec.

At higher condition which were down speed between 1.7 to 1.9 mm/sec. and current between 95 to 115 Amp, were studied. The results of these experiments were shown in Table 5.6, below. More details were explained in statistical analysis results. (Note: the down speed of 1.7-1.9 mm/sec. were used because it was the way to find out that at higher down speed, than 1.6 mm./sec, the specimen could be hardened to the required hardness or not. And the current between 95-115 Amp were studied because at the coil current of 120 Amp and down speed of 1.8 mm/sec., the surface hardness of specimen was over 60 HRC, shown in Table 5.2)

Table 5.4. Average value of surface hardness and hardness distribution at each depth by current fixed at 105 Amp.

Down speed (mm/sec.)		2	1.9	1.8	1.7	1.6
Surface hardness (HRC)		58.33	58.67	59	59	58.83
Hardness in HV at distance (mm.) from surface	0.1	652	675	680	678	682
	0.2	651	652	667	668	681
	0.3	644	649	642	658	683
	0.4	611	625	640	643	647
	0.5	584	623	621	636	632
	0.6	340	536	589	612	623
	0.7	311	318	438	557	588
	0.8	272	295	346	422	486
	0.9	248	254	266	286	344
	1	238	241	255	258	251
	1.1	237	235	241	248	248
	1.2	236	236	238	237	238
	1.3	238	235	233	237	237
	1.4	235	236	234	239	235
	1.5	238	235	233	235	235
	1.6	238	238	234	235	233

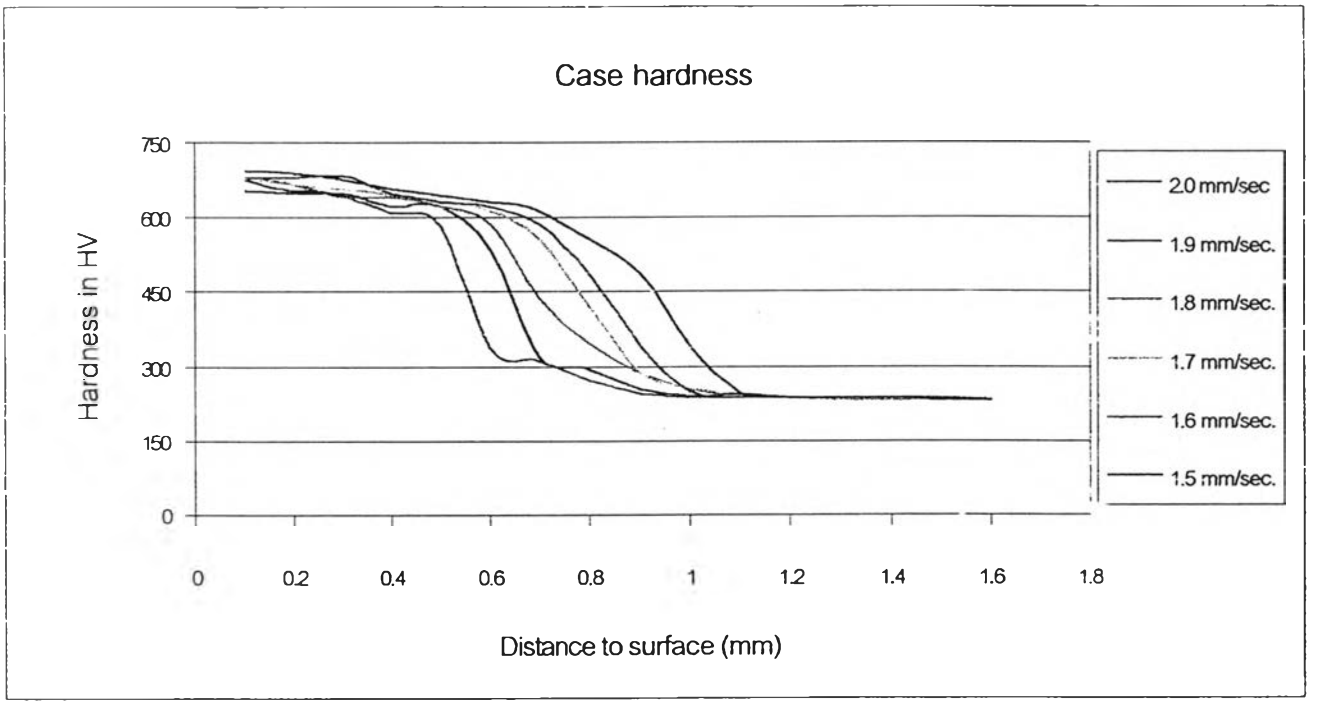

Figure 5.3. Hardness distribution of each down speed varied

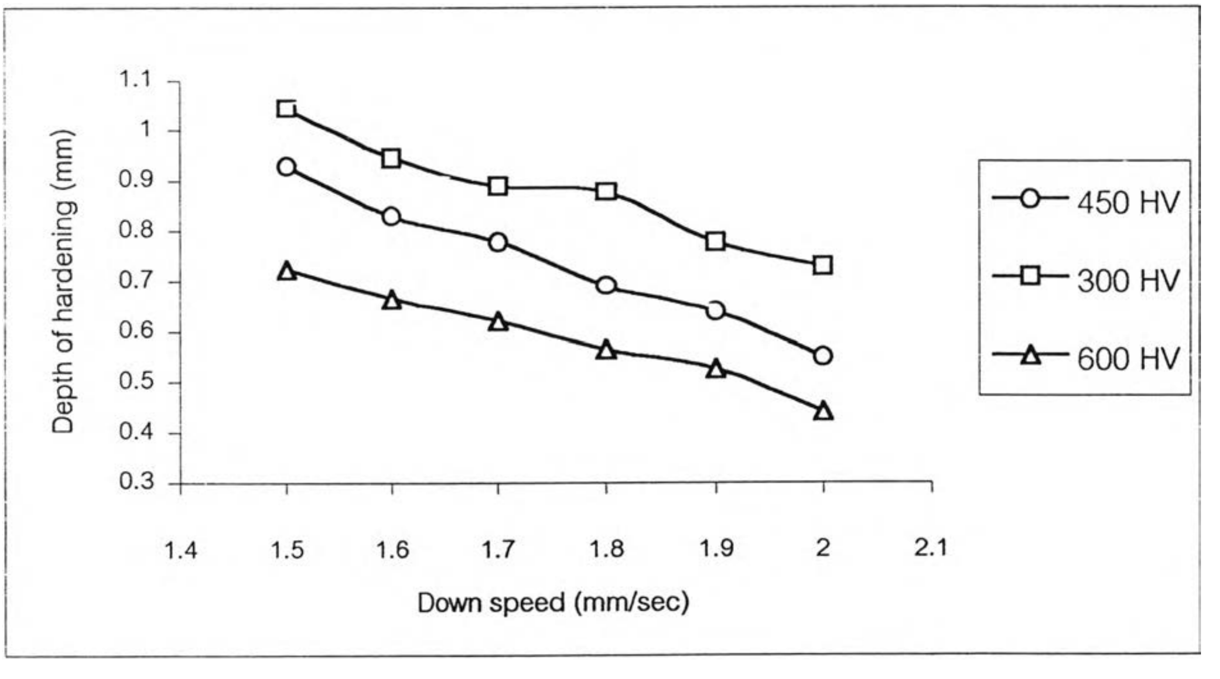

Figure 5.4. Relation of case depth and down speed at current of 105 Amp.

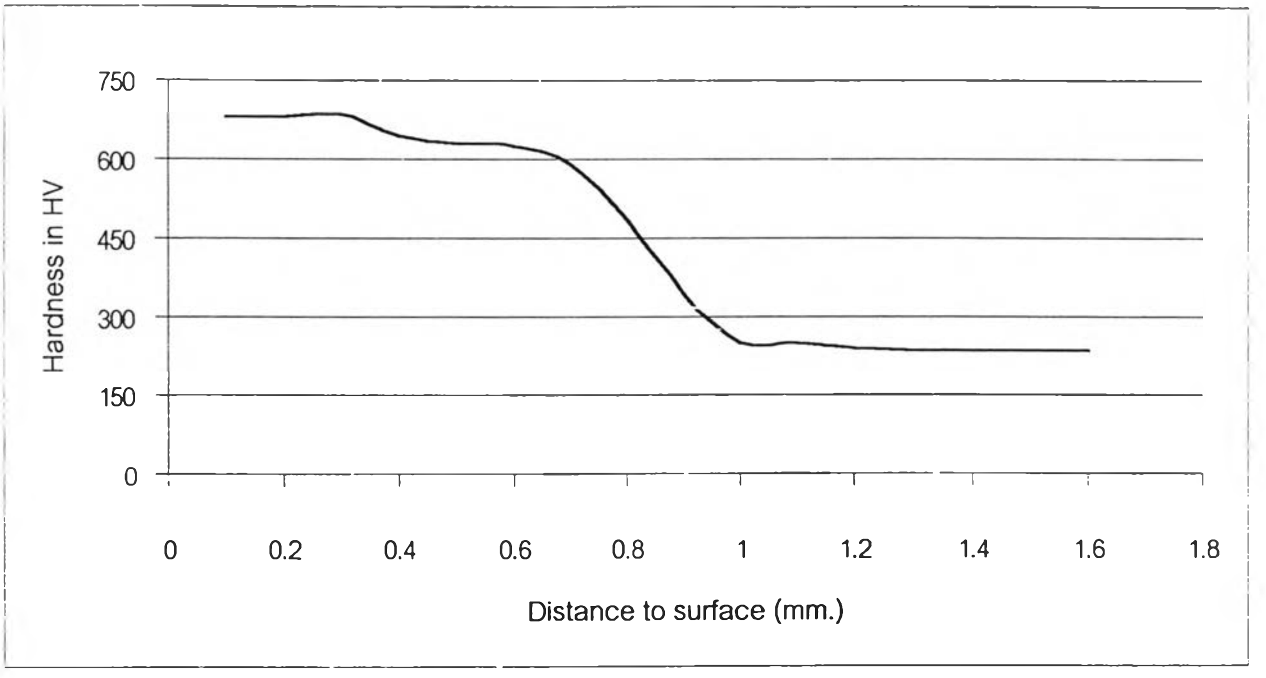

Figure 5.5. Hardness distribution from surface hardening to inner core at down speed 1.6 mm/sec. and current 105 Amp.

Table 5.5 Down speed and depth of hardening with hardness of 300, 450 and 600 HV

Down speed (mm/sec.)	Depth of hardening (mm.)		
	300 HV	450 HV	600 HV
1.5	1.04	0.93	0.72
1.6	0.94	0.83	0.67
1.7	0.89	0.78	0.62
1.8	0.88	0.69	0.57
1.9	0.78	0.64	0.53
2.0	0.73	0.55	0.44

Table 5.6. Average value of surface hardness and hardness distribution of the improvement.

Condition					
Current (Amp)		95	115	95	115
Down speed (mm/sec)		1.9	1.9	1.7	1.7
Surface hardness (HRC)		57.33	60.17	57.83	60.83
Hardness in HV at distance (mm) from surface	0.1	611	678	652	697
	0.2	611	676	644	685
	0.3	597	654	631	669
	0.4	558	632	613	658
	0.5	536	629	597	642
	0.6	339	609	511	640
	0.7	286	544	438	585
	0.8	247	398	334	529
	0.9	243	349	255	380
	1	241	245	238	261
	1.1	237	236	235	238
	1.2	236	238	238	237
	1.3	239	238	238	237
	1.4	239	239	238	239
	1.5	239	236	234	238
	1.6	237	236	234	237

From the data in Table 5.4 and 5.6, the influence of down speed on the surface hardness and the hardness at 0.8 mm. in depth can be drawn demonstrated by Figure 5.6 and 5.7 respectively. When the results from Table 5.4 and 5.6 were plotted between current and surface hardness, and current and hardness in depth at 0.8 mm of specimen, it could be demonstrated in Figure 5.6 and 5.7 respectively.

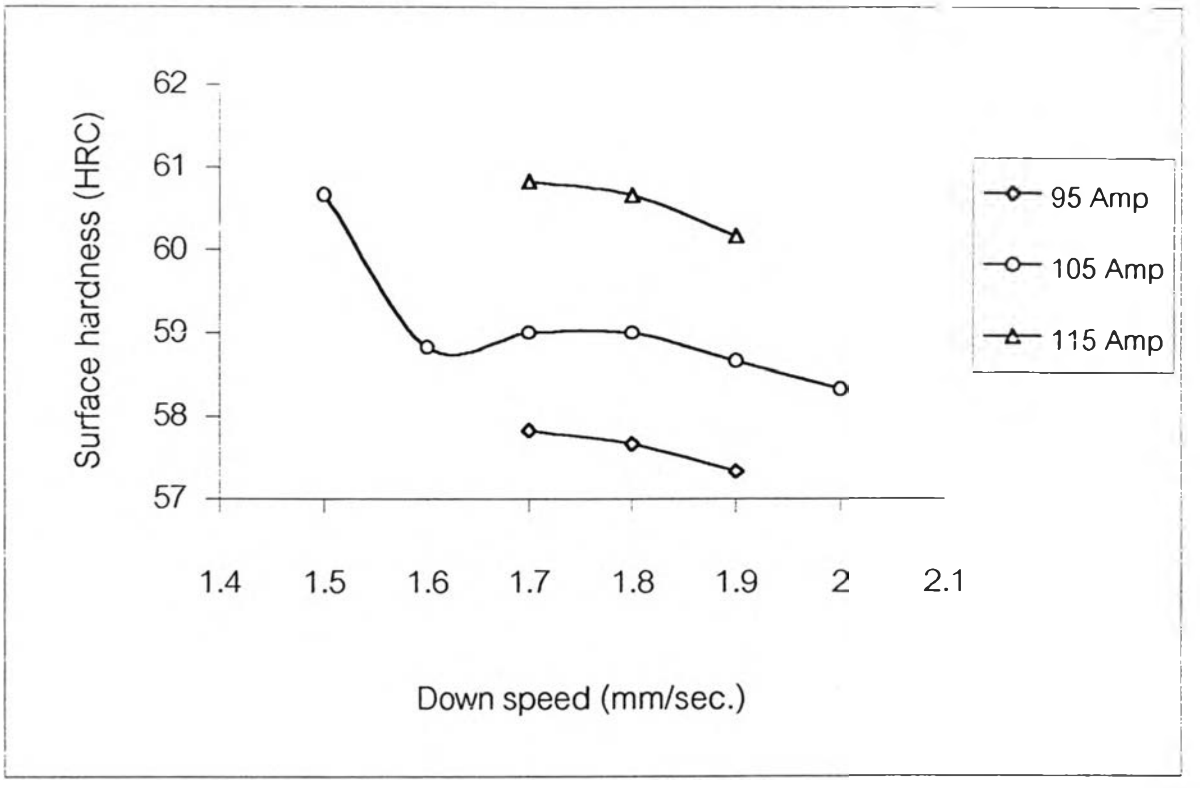

Figure 5.6. Relation of down speed and surface hardness

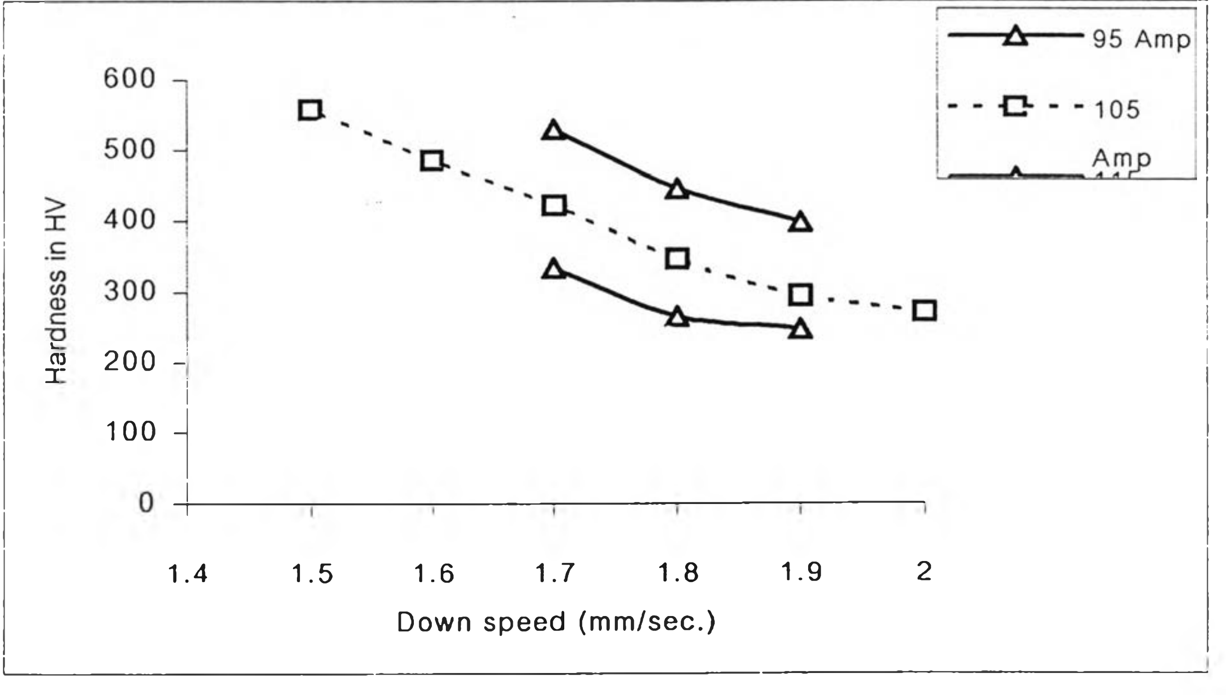

Figure 5.7. Relation of down speed and hardness in HV at 0.8 mm in depth

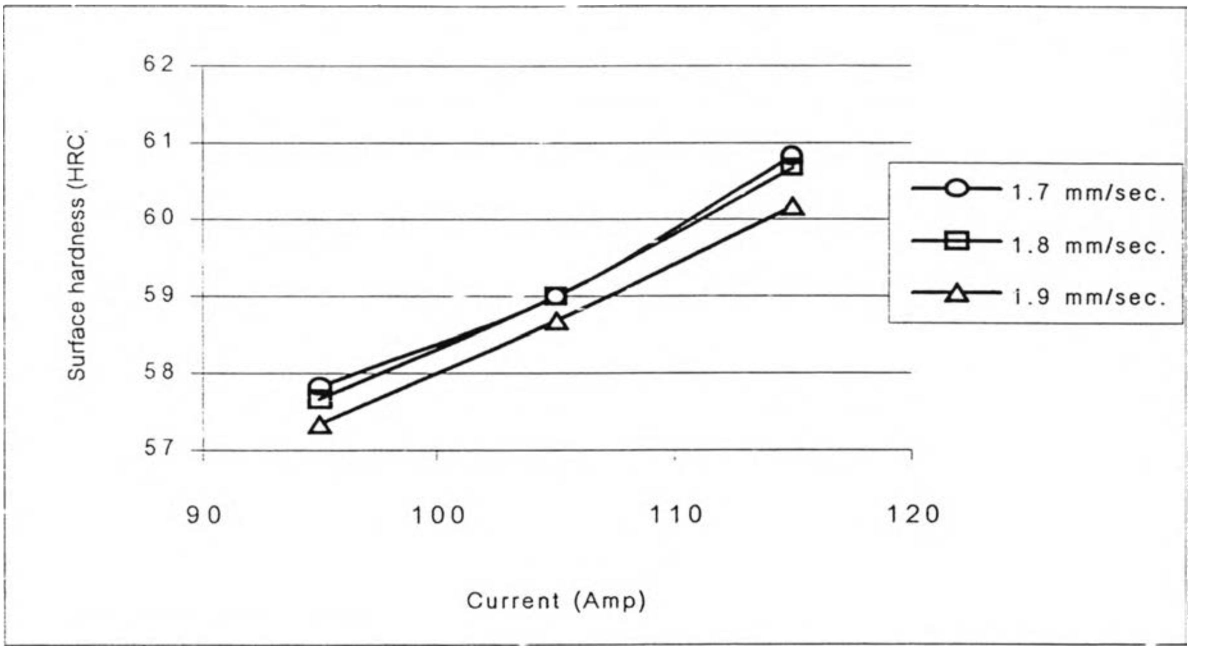

Figure 5.8. Relation of current and surface hardness

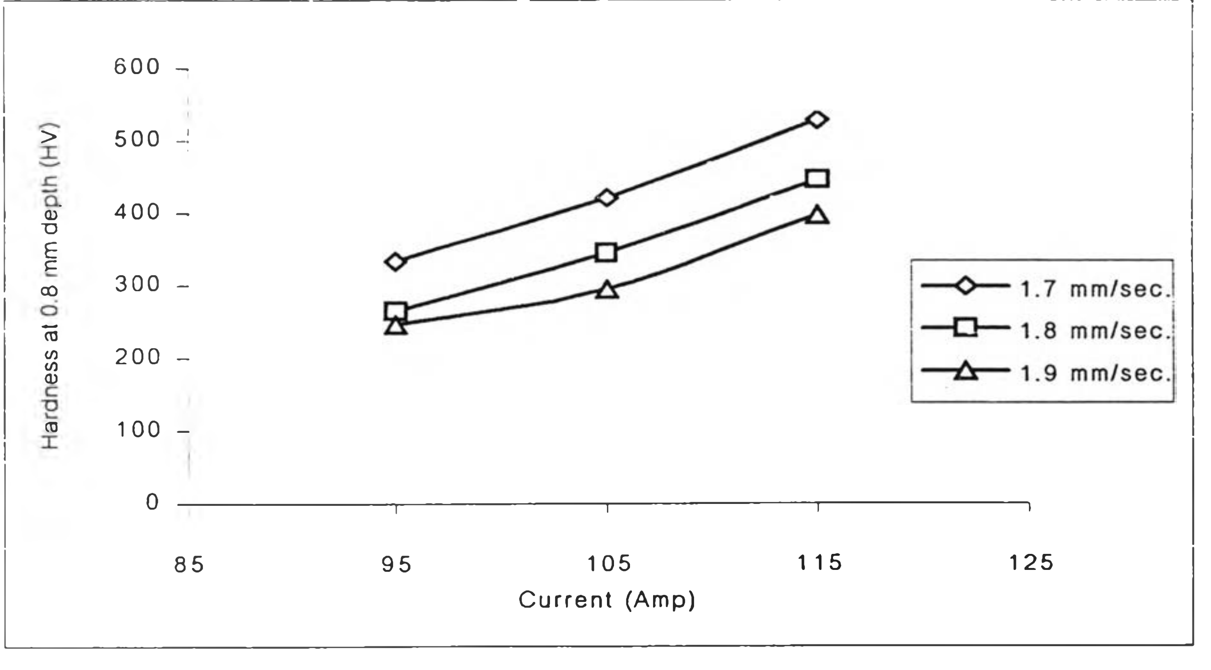

Figure 5.9. Relation of current and hardness in depth

5.3 Statistical analysis results

5.3.1 Analysis of Variance (ANOVA)

From the experimental data above, the result of analysis of variance could induce the influence of the factor affecting to the surface hardness and hardness in depth, which were:

1. Main effects are down speed and coil current
2. Interaction effect is the effect between the down speed and coil current

This ANOVA result illustrated which factor effect to the surface hardness and which factor effect to the hardness in depth. The result from the analysis of variance showed in Table 5.7 and 5.8.

Table 5.7. ANOVA (Factor effecting to the surface hardness) at 0.05 significance level

Source of Variation	Sum of Squares	Degrees of Freedom (ν)	Mean Square	Fo	$F_{\alpha,\nu}$
Down speed	1.24	2	0.62	7.09	3.55
Current	39.24	2	19.62	224.22	3.16
Interaction	0.09	4	0.0225		
Error	1.17	18	0.065		
Total	41.74	26			

From the table above, the influences of the down speed and current were

- The highest influence on the surface hardness was the current because it had the maximum value of F_0 being 224.22
- Down speed also had minor effect to the surface hardness (F_0 = 7.09)
- The interaction between down speed and current did not have the effect to the surface hardness.

Table 5.8. ANOVA (factor that effect to the hardness in depth) at 0.05 significance level

Source of Variation	Sum of Squares	Degrees of Freedom (V)	Mean Square	Fo	$F_{\alpha, v}$
Down speed	61365.63	2	30682.81	9308.27	3.55
Current	139913.9	2	69956.93	21222.89	3.55
Interaction	2014.37	4	503.59	152.77	3.26
Error	59.33	18	3.29		
Total	203353.2	26			

From the analysis of variance in table above, the influence of down speed and current to the hardness in depth were:

- The current had the maximum effect to the hardness in depth by the value of F_0 at 21222.89.
- The down speed also had high effect to the hardness in depth (F_0 = 9308.27)
- The interaction between down speed and current had minimum effect to the hardness in depth (F_0 = 152.77)

5.3.2 Regression

From the results shown in Figure 5.6 to 5.9, the new result of condition was improved by following. According to the customer specification, the maximum limitation of surface hardness was 60 HRC, and the hardness in HV at 0.8 mm. in depth was minimum 450 HV. From the relation of current and surface hardness in Figure 5.8, the surface hardness at 60 HRC was drawn a straight line as a limit of maximum surface. It will intercept at down speed 1.7, 1.8, and 1.9 mm/sec, and then they were projected to the x-axis, current. The value of current should be between 105 and 115 Amp. However, from the experimental result in Table 5.1, at each point at current between 105-115 Amp of down speed 1.8 mm/sec there had lower hardness at 0.8 mm in depth than 450 HV. According to Figure 5.4, the way to increase the depth of hardening was decreasing down speed. Therefore at the down speed 1.7 mm/sec were determined.

From the above analysis, the surface hardness and the hardness at 0.8 mm in depth at 110 Amp and down speed 1.7 mm/sec. were needed to find out.

The multiple regression was used for test the relationship between surface hardness and current from Figure 5.8, and the hardness in depth and current from Figure 5.9. The results from the multiple regression obtained the multiple regression equations as shown follow.

Equation 1:

$$\text{Surface hardness (HRC)} = f(\text{Current, Down speed}) = 48.019 + 0.147*(\text{Current}) - 2.483*(\text{Down speed})$$

Equation 2:

$$\text{Hardness at 0.8 mm. (HV)} = f(\text{Amp, Down speed}) = 478.48 + 8.783*(\text{Current}) - 575.55*(\text{Down speed})$$

From the equations above, the current of 110 Amp and down speed of 1.7 mm/sec. will have the surface hardness of 59.97 HRC and the hardness at 0.8 mm in depth of 466.175 HV. This result showed that if the current is 110 Amp and the down speed is 1.7 mm/sec. the oil pump shaft would be hardened to the desired hardness.

At this condition three experiments were made to investigate whether the specimen can reach the desired hardness or not. The experimental results were shown in Table 5.9, and the hardness distribution was shown in Figure 5.10.

Table 5.9 Results of surface hardness and hardness at 0.8 mm in depth at current 110 Amp, down speed 1.7 mm/sec.

Surface hardness (HRC)		60	59.6	59.7
Hardness in HV at distance (mm.) from surface	0.1	689	691	692
	0.2	685	685	684
	0.3	662	661	667
	0.4	661	661	564
	0.5	654	658	657
	0.6	613	621	618
	0.7	557	554	546
	0.8	481	475	473
	0.9	394	391	387
	1	279	276	281
	1.1	248	251	247
	1.2	237	239	238
	1.3	247	236	238
	1.4	238	246	236
	1.5	241	237	243
	1.6	235	236	235

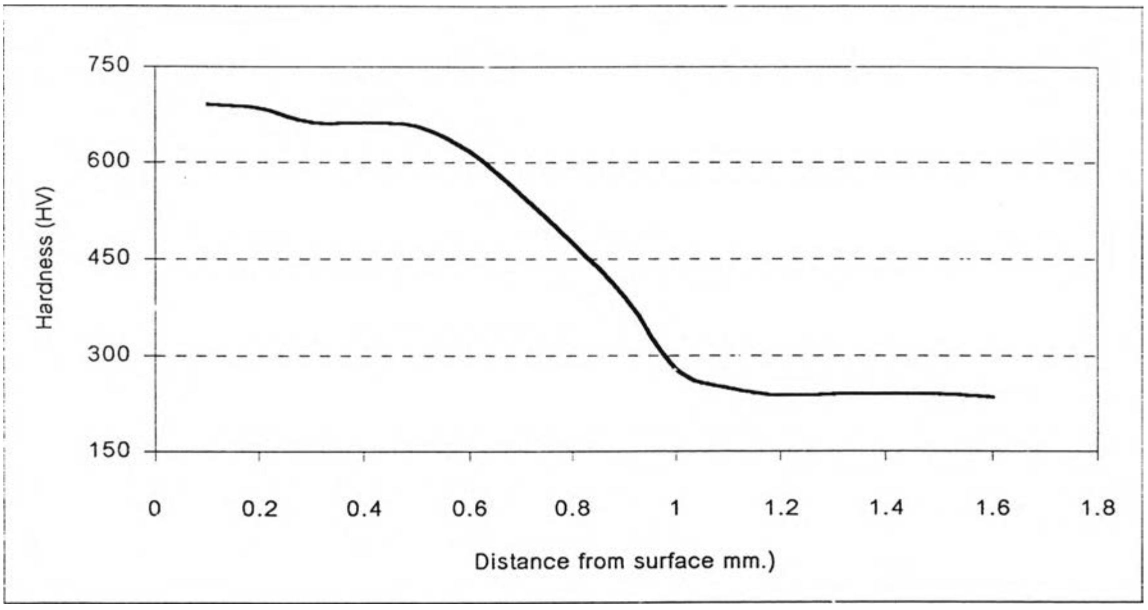

Figure 5.10. Average values of hardness distribution of current 110 Amp, down speed 1.7 mm/sec.

5.4 Microstructure result

In figure 5.11, it showed the microstructure of specimen before induction hardening. It consisted of a mixture of pearlite and ferrite.

Figure 5.11. Microstructure of the specimen before induction hardening

Before induction hardening, the specimen was speculated by G.M. machine. It illustrated that each point from surface layer to inner core had a mixture of pearlite and ferrite. Therefore, it had the lowest hardness compared with after induction hardening.

Figure 5.12 showed the variation of microstructure of the specimen at the current of 105 Amp and down speed of 1.8 mm/sec., before improvement.

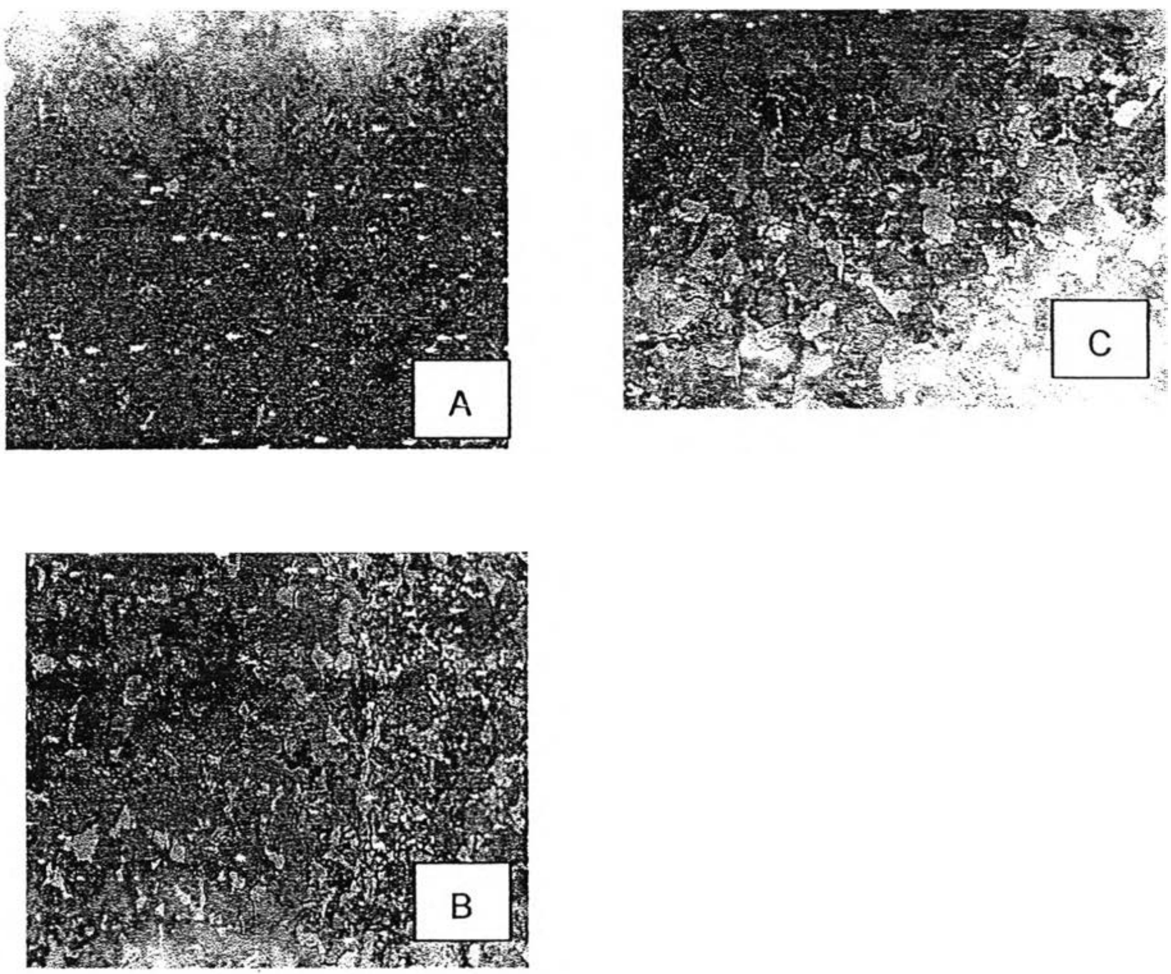

Figure 5.12 Microstructure of specimen at current 105 Amp, and down speed 1.8 mm/sec. from surface layer to inner core in figure A to C respectively.

The surface hardening layer shown in Figure 5.12(A) had hardness between martensite and pearlite, however more closer martensite. The possible reason for such morphology and structure could be owing to the rapid heating. It was in so short a period of time that the skin effect caused the surface of the work-piece only partially austenitized and soon followed immediately by direct quenching. There was no sufficient time for atomic diffusion in austenitic area. So the result was formation of a martensite structure which resembled fine pearlite in morphology but possessed the hardness of martensite. On the contrary the structure in the inner core remains unchanged as a mixture of pearlite and ferrite after the treatment. The results of hardness test showed no difference in comparison with that of before hardening.

By increasing the current intensity and decreasing down speed, the case depth as well as surface hardness wolud be apparently increased. Figure 5.13 was the micrograph of hardened surface layer of the specimen after improvement. In this figure, there was no ferrite could be identified as that in Figure 5.12(A). The sequential change of microstructure from outer surface to the inner core begins with martensite formation in hardened surface layer, in Figure 5.13(A), and then turns out gradually to be fine pearlite in a little inside area, in Figure 5.13(B). By further deeper inside, the existence of remained unchanged ferrite appeared as white island in structure causes hardness to decrease. The structure of fine pearlite disappeared gradually and then a mixture of pearlite with ferrite was observed, shown in Figure 5.13(C) and (D) respectively. The hardness distribution is shown in Figure 5.13.

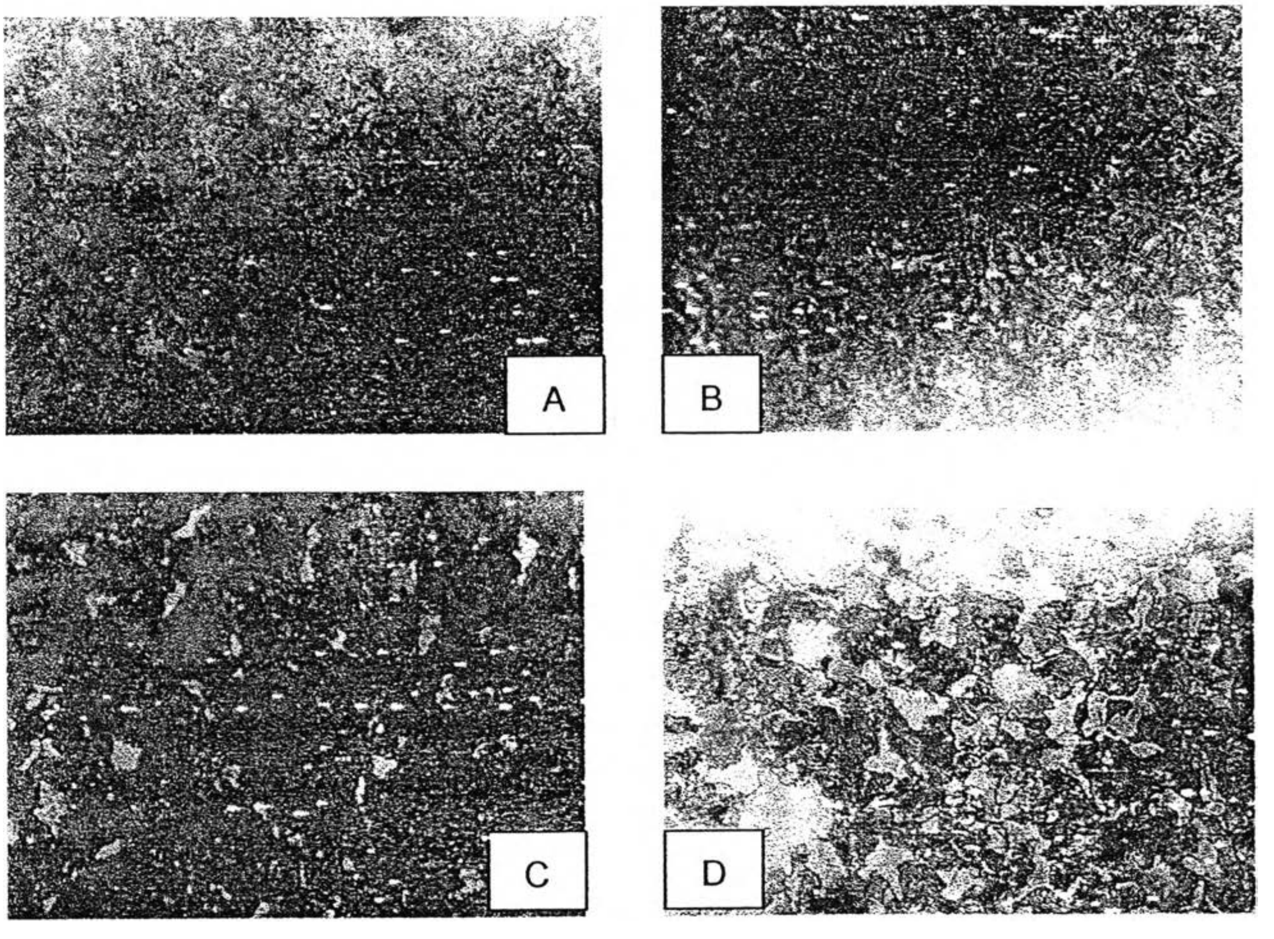

Figure 5.13. The microstructure of the specimen at current =110 Amp and down speed = 1.7 mm/sec. from outer layer to inner core in figure A to D respectively