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Controlling hardness, shape, and size distortions in gas carburized steel materials

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ABSTRACT

Carburizing, though a widely used industrial thermo chemical diffusion process, it is associated with the problem of shape and size distortion in the carburized parts. These distortions are troublesome as they adversely affect the performance of the parts in terms of life, and trouble free operation. The main objective of our present work is to optimize the distortion level, optimum case depth, and surface hardness value of the carburized parts made of EN 353 material. Taguchi's mixed level series Design of Experiment was selected for optimization. The significance of our study was that all the three stages of carburizing (Pre carburizing, Carburizing and Post carburizing) were considered for optimization. An orthogonal array and ANOVA were employed to investigate the influence of major parameters on the three response variables namely Distortion level, Surface hardness and Case depth and optimum conditions were arrived at by applying high penetration depth, high hardness and low distortion are better as the strategies.

Introduction

Carburizing is a widely used case hardening process for low carbon steels. In this process carbon is dissolved in the surface layers of low carbon steel part when it is held at a temperature (850ºC to 950ºC) sufficient to bring steel to its austenitic phase followed by quenching and tempering to form martensitic microstructure [1]. But, the main problems in the Gas carburized components (e.g., pinion used in power steering assembly) are shape and size distortion. These distortions in the components are troublesome to the manufacturers as they adversely affect the performance of the mentioned components in terms of life, trouble free operation, and noise of operation. As reported by Dong-hui, Xu and Zhen –Bang Kuang (1996), there exists a definite link between distortion and the initiation of fatigue failure. If the distortion is controlled within the design tolerance limit in the post hardening processes, rejections can be eliminated or reduced to a large extent. This will result in cost saving and increase in productivity.

While shape distortion in carburized steel part is due to the induced residual stresses, size distortion is due to structural transformations in steel. Shape distortion or change occurs in gas Carburizing process due to the presence of retained austenite (Shen – Chih Lee and Weio-Youe Ho, 1989). Cooling carburized steels to sub-room temperature is a processing approach sometimes used to reduce the retained austenite content in the case region of carburized and hardened steels and hence distortion. Such a cooling treatment is referred to as sub-zero cooling and is used for carburized and hardened components that require high precision and stable dimensions through out their service life [3]. Size distortion requires different approaches to either eliminate or reduce it. Expansion and contraction of the material, which happen during the carburizing process, alternatively results in size distortion. Many literatures indicate that the following are some of the reasons for distortion.

❖Rapid heating
❖Wrong stacking or fixturing of parts
❖Increase in grain growth with increase in case depth
❖Severity of quenching

The final quality of a part depends on the correct combination of case depth and level of hardness without any thermal damage including distortions. The carbon dissolved in the austenite is the decisive factor determining surface hardness. When the carbon concentration at the surface of conventional alloy case-hardening steels exceeds 0.70%, the M_s temperature falls steeply and the amount of retained austenite after quenching increases and the hardness decreases. If the surface layer of the steel contains the appropriate concentration of carbon for maximum hardness, the quenching temperature is of minor importance to the hardness provided that the grain size is not altered. By varying the quenching temperature of an 'over-carburized' steel it is possible to control the amount of carbon going into solution and hence the amount of retained austenite which, in turn, affects the hardness (Robinson, G.H., 1957).

The depth of hardness penetration depends on the carbon content of the carburized layer. It also depends on the dimension of the part (Beumelburg, W., 1964). In the hardening process if martensite is the only phase formed after quenching, the depth of case hardening would be equivalent to a depth of carbon penetration down to 0.40% C. This would agree well for small parts but as the section dimensions increase, the rate of cooling decreases and hence the conditions necessary for the formation of martensite are changed.

Case-hardened steels are tempered at temperatures generally around 160-220°C. Carburized microstructure is almost always tempered to transform the unstable and brittle martensite into

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stable tempered martensite. Tempering decreases residual stresses and this is promoted by increasing the tempering temperature. Temperatures below 160°C should not be used, particularly if a grinding operation is to follow, since grinding cracks develop very easily. The hardness falls quite rapidly when the steel is tempered between 160°C and 200°C. If a hardness of 60HRC is required, the tempering temperature should not be higher than 180°C (Thelning, 1984).

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 case-hardened steels as a result of quenching. The development of residual stresses, final microstructure and mechanical properties in the case 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.[4]

Anand M Deshpande et al.,(2003) analyzed the optimization of carburization profile for minimizing the process cost and reported that Gas carburizing is a complex process in itself as a number of variables affect the success of the process and quality of the components. Mitra (2004), demonstrated a cost model based optimization of carburizing operation and used Furnace Temperature, Carbon potential, Quenching time, tempering temperature, Preheating and tempering time as the influential variables.

An industrial survey indicates that there is a rejection of 10-12% of case hardened components due to various defects like crack formation, over hardening, change in size and shape etc, and the extent of rejection can be kept to a minimum by closely monitoring the process and installing proper quality control measures.

In the case of surface treatment processes this is possible by controlling the process variables. If the process variables are optimized from the point of view of the obtainable material characteristics, it will be a good measure. Thus, determination of process variables lies in the proper selection and introduction of suitable limit design concept at the earliest stage of the process and product development cycle that will result in the quality and improved productivity.

In spite of the extensive studies that have been carried out so far, controlling the correct depth of hardness in induction hardening process remains difficult. Several methods are being applied to obtain the correct value of required hardness thickness. Relationship among the influential variables can be obtained in optimum value using intelligent techniques.

The present work addresses the gap in the studies that exist in obtaining the quality heat treated components using the experimental design approach for new products [5]. Taguchi's mixed level series design of experiments approach has been used to accomplish the objective of finding out the level at which all the controlling process parameters have to be kept in order ensure that the carburized part is distortion free and at the same time has the hardness and depth of hardness as specified.

Experimental Details

Gas carburizing experiments have been conducted on the automobile power steering pinion, which is made up of EN353 steel material, as shown in figure 1. Care has been taken in obtaining the final dimensions of the part as close to the designed dimension as possible. This is required to keep the time for heat treatment the shortest. If it is not taken care of before the carburization, it may lead to severe distortions in the carburized part.

Fig- 1 Pinion

The pinion material selected for investigation was EN 353 [C = 0.18%, Mn = 0.86%, Ni = 1.14%, Cr = 1.07%, Mo = 0.12%]. The experiments were conducted in a Methanol-Acetone Unitherm Gas Carburizing Pit Furnace with oil as quenching medium.

Designs Of Experiments

Taguchi's mixed level series design of experiments approach has been adopted to conduct the experiments. The entire set of experiments was conducted mainly to have control on the obtainable case depth, hardness without the size and shape distortion. So, the response variables for the experiments were all the four mentioned variables.

Through preliminary experiments and the expertise available in the work place where the experiments have been conducted, we could zero in on the process variables which have direct impact on the selected response variables.

i. Carburizing Temperature (3 Levels) - A
ii. Carbon Potential (3 Levels) – B
iii. Tempering Temperature (3 Levels) - C
iv. Quenching Time (3 Levels) - D
v. Preheating (2 Levels) – a pre carburizing process - E

To make the experimental investigations more practicable interactions as given below,

i. Carburizing Temperature (A) Vs Carbon Potential (B)
ii. Carbon potential (B) Vs Tempering Temperature(C), have also been taken into account.

For conducting the experiment, orthogonal array (Taguchi's Mixed Level series Method of Experimentation) was chosen. A L_{18} (2^1, 3^{5-7}) orthogonal array design of experiment was adopted and the selection of orthogonal array, formation of orthogonal array is detailed in Table 1. The process variables as decided upon are listed below and their value details are given in table 2.

- Interaction between Furnace Temperature and Carbon Potential
- Interaction between Tempering Temperature and Carbon Potential

The experiment was conducted taking 5 samples (as shown in figure 1) for each set. The experiment was conducted using Randomization Technique to avoid experimental error with the control factors and their levels as per the Table 2.

Degrees of freedom (DOF) for each factor are arrived at from the number of levels of them in the experiments. i.e.,

DOF = Number of levels of the factor – 1

Following the expression shown above, the DOF of all process factors considered in the present experiments are arrived at and the same are given below:

DOF for factor A = (3-1) = 2
DOF for factor B = (3-1) = 2
DOF for factor C = (3-1) = 2
DOF for factor D = (3-1) = 2
DOF for factor E = (2-1) = 1

Similarly, the degrees of freedom for the interactions are also given below:

DOF for AxB = (2x2) = 4

DOF for BxC = (2x2) = 4

From the degrees of freedom of the individual process factors, the degrees of freedom for the experimental design are arrived at as given below:

DOF for experimental design = Sum of all individual process factor DOFs = 17

DOF available in an Orthogonal Array = 18-1 = 17.

After conducting the experiments, the response variables were measured as detailed below. The surface hardness was measured with Rockwell Tester in HRA scale. Case depth was found through Visual Metallurgical Examination.

The size distortion was measured using Mechanical Dial Gauge (Run out variation). Quantification of the shape distortion of the pinion was done by measuring the variation in the helix angle of the pinion using Gear Tester. The resultant measurements are tabulated in Table 3.

From the experimental result, the average effects of process variables, as given in table 2, on the obtainable surface hardness and case depth have been arrived at and the same are presented in Table 4. The sample calculation for average effect of process variable, furnace temperature (Level 1) on surface hardness is given below:

Average effect = (79+79+81+80+81+81)/6 = 80.16 HRA

Influence of process variables on surface hardness case depth

ANOVA analysis is carried out to determine the influence, in terms of percentage contributions, of each of the main variables on the obtainable surface hardness and case depth in the sample materials used in the conduct of the experiments. Table 5 shows the results of percentage contribution of each of the process variables obtained through ANOVA. For clarity purpose, a sample calculation in arriving at the percentage contribution of the variable, namely, furnace temperature, on case depth obtainable in the hardening process is given below:

Correction factor, C.F = $[\sum yi]^2$ / Number of Experiments

= $[0.8+0.9+\ldots..0.8]^2$ /18 =0.311

Total sum of squares, SST = $\sum yi^2$ – C.F =11.98-0.311 = 11.569

Sum of Squares of Variables,

Variable A, SSA = $[\sum y1^2/6+\sum y2^2/6+\sum y3^2/6]$ – C.F

= [0.571+0.70+0.518]-C.F

= 1.398

Percentage contribution of variable, A

= (SSA/SST)*100

= (1.398/11.56) *100 = 12.08%

In the same way the percentage contributions of other variables on case depth are calculated and the total contribution is arrived as given below:

Total contribution of variables, (A+B+C+D+E+)

= (12.08+37.86+12.56+12.72+13.47)

= 88.61%

∴ Error =11.39%

Optimum condition with respect to the values or levels at which all the process variables under consideration have to be maintained for obtaining higher surface hardness and case depth is identified from the results of average effect of the process variables found out from the experiments and given in table 4. The values or the levels of each of the variables for optimum condition are listed in the table 6.

Results and discussion

The present work is carried out basically to identify and determine the influence of the major process variables involved in the gas carburizing surface hardening process on the obtainable hardened case depth, hardness, and distortion (shape and size) in the treated manufactured components. In the present instance, the pinion used in the automobile steering wheel mechanism is considered for study. Experiments were conducted following Taguchi's Mixed Level series Design of Experiment with interaction effect. The test results were subjected to ANOVA. The analysis indicates that the Carbon potential is having more influence (35%) on the case depth, hardness and distortion, whereas, the percentage contribution of other process variables are minimal only. In the present study, it was found that no abnormal change of shape in the samples subjected to surface hardening process.

The experiments conducted also helped in identifying the optimum process condition, which is essential for achieving expected results on the manufactured components. This was done by employing the following two strategies:

a) Higher is better, i.e., Higher surface hardness and higher case depth.

b) Lower is better, i.e., Lower run out and Helix angle variation for lower distortion.

As a validation, experiments were conducted on the actual components to ensure the dependability of the results obtained in this work. It was found and verified with the floor engineers that the results are more than satisfactory that is with 95% confident level.

Conclusions

This work is aimed at finding the ways and means of reducing the defects which may come up due insufficient surface hardness or case depth or distortion on the manufactured components subjected to Gas carburization process through the application of Taguchi's Mixed Level series Design of Experiment with interaction effect for process optimization. It could be identified, from the study; Carbon potential has more influence on the surface hardness and case depth of the Gas Carburized components. The study also helped to find out the optimum process condition to obtain high hardness, high case depth with low distortion. The optimum condition is:

Preheating – Required

Carbon Potential – 0.95mV

Furnace Temperature – 930º C

Quenching Temperature – 70º C

Tempering Temperature – 130º C

The confirmation of experiment shows that the experimental observations are within 95% confident level. The error in the experimental analysis is very low.

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Table -1. L_{18} (2^1, $3^{5-7)}$ orthogonal array used for experimentation

Trial	A	B	AxB	C	BxC	D	E
1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2
3	1	1	3	3	3	3	3
4	1	2	1	1	2	2	3
5	1	2	2	2	3	3	1
6	1	2	3	3	1	1	2
7	1	3	1	2	1	3	2
8	1	3	2	3	2	1	3
9	1	3	3	1	3	2	1
10	2	1	1	3	3	2	2
11	2	1	2	1	1	3	3
12	2	1	3	2	2	1	1
13	2	2	1	2	3	1	3
14	2	2	2	3	1	2	1
15	2	2	3	1	2	3	2
16	2	3	1	3	2	3	1
17	2	3	2	1	3	1	2
18	2	3	3	2	1	2	3

Table -2. Control factors/ Process variables with their levels

Sl. No	Factors	Level 1	Level 2	Level 3
1	Furnace Temperature (A)	900º C	920º C	930º C
2	Carbon Potential (B)	0.75mV	0.85mV	0.95 mV
3	Tempering Temperature (C)	130º C	150º C	180º C
4	Quenching Temperature (D)	35º C	50º C	70º C
5	Preheating (E)	Yes	No	No

Table -3. Experimental result for carburized EN 353 steel material

Sl. No.	Case Depth in mm	Hardness in HRA	Size Distortion			
			Helix *BHT in radians	Helix *AHT in radians	Run out in microns	
					*AQ	*AT
1	0.8	79	30.94	32.98	110	150
2	0.9	79	30.92	33.05	170	170
3	0.7	81	30.99	33.20	100	70
4	0.8	80	30.95	33.32	210	180
5	0.8	81	30.99	32.99	240	250
6	0.9	81	30.90	32.99	370	270
7	1.0	82	30.95	33.02	320	360
8	0.8	80	30.94	33.05	270	190
9	0.7	79	30.91	32.95	340	270
10	0.7	79	30.89	32.99	280	170
11	0.9	81	30.99	33.01	190	160
12	0.9	81	31.00	33.30	280	170
13	0.9	82	30.95	32.82	170	130
14	0.8	79	30.88	33.25	210	140
15	0.8	79	30.96	33.02	220	190
16	0.7	81	30.89	33.22	170	170
17	0.7	82	30.90	32.90	280	160
18	0.8	81	30.92	32.99	270	210

***BHT - Before Heat Treatment,** ***AHT - After Heat Treatment**
***AQ - After Quenching,** ***AT - After Tempering**

Table - 4 Average effects of process variables on surface hardness and case depth

Variables	Level 1		Level 2		Level 3	
	Surface Hardness	Case depth	Surface Hardness	Case depth	Surface Hardness	Case depth
Furnace temperature	80.16	0.816	80.33	0.78	80.66	0.833
Carbon Potential	80.10	0.816	80.166	0.783	80.83	0.833
Tempering Temperature	80.5	0.8166	80.33	0.8155	80.33	0.80
Quenching Temperature	73.83	0.783	80.5	0.816	80.83	0.833
Preheating	80.16	0.816	73.66	0.716	-	-

Table - 5 Percentage contribution of each variable on surface hardness and case depth

Variables	Surface Hardness	Case depth
	16.82	12.08
Furnace temperature	34.61	37.86
Carbon Potential	9.60	12.56
Tempering Temperature	12.21	12.72
Quenching Temperature	14.47	13.47
Preheating	12.26	11.39

Table -6 Optimum conditions for surface hardness and case depth

Variables	Surface hardness and Case depth
Furnace temperature	930°C
Carbon Potential	0.95mV
Tempering Temperature	130°C
Quenching Temperature	70°C
Preheating	Required (YES)