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Experimental analysis of thermal distortion in thermo-chemical treatment

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ABSTRACT

Gas carburizing is the most widely used surface hardening process for number of automobile and other heavy duty machinery components made up of ferrous material. It is a complex process and many literatures shows that the defects are due to shape distortion and volume change. This work attempts to minimize the extent of those defects in gas carburized automobile parts through Taguchi’s DOE approach. The optimum combination of parameters which will alleviate the distortion problems are obtained through the response graph method. The results are compared with that obtained from S/N ratio method. The studies are validated through experiments. In addition the present study shows that the introduction of optimal conditions and elimination of straightening operation saves time and money.

Introduction

Carburizing, which is widely used for case hardening of number of automobile components made up of low carbon steel, poses some serious problems in the form of shape and size distortions. Anand M Deshpande et al.,(2003) stated 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. Further, they reported that the rejections due to the distortion defects lie in the range of 10 to 12%. More than the rejections the defects are troublesome to the manufacturers as they adversely affect the performance levels of the carburized components like, service life of the components, trouble free operation, and noise. Dong-hui, Xu and Zhen –Bang Kuang (1996) reported that there exists a definite link between distortion and the initiation of fatigue failure. If the distortions due to the hardening process could be controlled within the allowable limit, rejections can be eliminated or reduced to a large extent and the trouble free long life functioning can be ensured. This in turn will result in increased quality and productivity, cost saving, and customer satisfaction.

Among the shape and size distortions, the shape distortion in carburized steel part happens because of induced residual stresses. Shen – Chih Lee and Weio-Youe Ho (1989) showed that the presence of retained austenite in the gas carburized component results in shape distortion. The problem of retained austenite can be overcome to some extent by cooling the carburized steels components to sub-room temperature. Where ever, high precision and stable dimensions through out the service life of the hardened components are required such a cooling treatment, which is referred to as sub-zero cooling. Unlike shape distortion, size distortion is caused by the structural transformation that happens in the steel material during the carburizing process. The size distortion is caused by alternate expansion and contraction of the material. Size distortion requires different approaches to either eliminate or reduce it. Some of the reasons for size distortion, as indicated by Thelning, (1984) are,

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

The final quality of the carburized component can be assessed by the case depth and level of hardness that too without any thermal damage including distortions. Level of hardness is determined by the dissolved carbon in the austenite phase. The steep fall in Ms temperature due to the presence of carbon in excess of 0.70% controls the amount of retained austenite and thereby affects the hardness level. It means that if it is ensured that the steel material contains the right amount of carbon for attaining the maximum hardness the above problem can be overcome to a large extent. Robinson, G.H. (1957) showed that the level of hardness can be effected by varying the quenching temperature of an ‘over-carburized’ steel to have a control on the amount of dissolved carbon and hence the amount of retained austenite.

The hardness penetration depth depends on the carbon content in the carburized layer and the dimension of the part (Beumelburg, W., 1964). When martensite is the only phase formed after quenching, the case hardening depth is measured to a depth of 0.40% C carbon penetration. But, the transformation as mentioned above holds good for smaller parts only. For larger sections the conditions would be different because of the change in the cooling rate of the larger section.

Tempering, after carburizing, decreases residual stresses and this is promoted by increasing the tempering temperature. But, tempering causes some reduction in the hardness and it falls quite rapidly when the tempering temperature falls between 160°C and 200°C. It has been reported (Thelning, 1984) that when a hardness in the range of 60HRC is required, the tempering temperature should not be higher than 180°C.

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The extent of residual stresses, final microstructure, and mechanical properties of the case hardened steel material depends on the complex interactions among its composition, component size and geometry, carburizing and subsequent austenitizing process parameters., heat transfer associated during quenching and time and temperature parameters of tempering.

Even though, industrial surveys say that there is 10-12% rejections in the case carburizing process due to various defects like crack formation, over hardening, change in size and shape etc, the rejections can be controlled by installing proper quality control measures. Controlling measures largely depend on 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. If the levels of the process variables can be determined at the earliest stage of the process and product development cycle using suitable limit design methods, it will greatly help in reducing the rejections and increasing productivity.

In spite of the extensive studies that have been carried out so far, controlling the correct depth of hardness in carburizing process remains elusive. Several methods are being adopted to obtain the correct depth of hardness. Intelligent techniques may be used to find the effect of various process parameters on hardness and depth of hardness.

The present work addresses the problem of obtaining quality heat treated components using the experimental design approach for new products.

Taguchi's mixed level series design of experiments approach has been used for finding out the level at which the controlling process parameters have to be kept to ensure distortion free carburized part with required hardness and depth of hardness.

Control factors in Gas carburizing

Through the initial stages of experiments, it has been identified that the following are the parameters of carburizing process which have considerable effect on achieving the specified characteristics on the components heat treated.

- Temperature
- Time
- Composition of the carburizing atmosphere

Other variables that affect the amount of carbon transferred to the heat treated components include the state of the carburizing atmosphere and the composition of the material of the component subjected to heat treatment.

The Composition of the carburizing atmosphere how does it react while the carburizing process is going on can be explained as follows:

Gases present in the furnace may be either carburizing gas or decarburizing gas or neutral gas. Methane is the most common gas used in gas carburizing.

Even when higher homologues are used, they break down into carbon and methane. Methane or propane is burnt in a controlled manner producing a gas of the following composition. Controlled additions of methane or propane are then added to the gas to increase the carbon potential.

N_2: 35-40%, H_2: 40-45%, CO: 15-25%, CO_2: 0.1-1%, and CH_4: 0.5- 1.5%

Methane does not carburize steel directly, and carburizing takes place as per the reactions shown in equations 2.1 and 2.2.

$CH_4 + CO_2 \rightarrow 2CO + 2H_2$ (2.1)

$Fe + 2CO \rightarrow FeC + CO_2$ (2.2)

The balance of the constituents of the carburizing atmosphere is maintained by the water and gas reaction as shown in equation2.3.

$CO + H_2O \rightarrow CO_2 + H_2$

(2.3)

Carburizing of the surface of the component can be sustained only if the carbon potential of the furnace atmosphere is greater than the carbon potential of the surface of the component. It is the difference in carbon potential that provides the driving force for carbon transfer to the parts.

Distortions in carburizing

Distortions have always presented difficulties to manufacturers and end users of the many varieties of heat treated steel parts. The dimensional changes in the carburized and quenched components have proved to be costly and troublesome to manufacturers for long.

The term distortion, in the present context, describes the dimensional changes brought about in the heat treated components because of the complex internal stress conditions which prevail after processing. Distortion can be classified as,

1. Volume change - due to transformation stresses.
2. Dimensional change - due to thermal stresses

Straightening

Due to heat treatment the pinions get deformed (bend&helix unwind). Straightening operation is done to remove the bend in a 5 ton hydraulic press. Due to straightening operation a lot of money and man value is consumed which considerably adds to the total cost. The elimination of straightening which is done after tempering saves Rs. 7.2 Lacs (Euro12, 000).

Design of Experiments

Fundamental to have better control on the processes like Carburizing is to identify the critical factors which have profound effect on the quality of the output. For the identification of critical factors (which needs to be controlled with in narrow limits) and to identify the optimum level of the critical factors, well planned methodology is to be selected at the design stage of the component itself. Here, it has been done by applying Taguchi's technique.

Experimentation

Experimental investigation of gas carburizing process has been carried out using Taguchi's Design of Experiments Approach.

Raw Material Selection

The raw material used for pinion manufacturing is EN 36A (30 Ni Cr2 Mo28).

Machining operations

The various machining operations performed to manufacture are listed below:

❖ Parting, Facing and centering, Turning, Hobbing and Rolling

Heat Treatment Process

The carburizing furnace used for this purpose is pit type vertical sealed removable type retort furnace. The gases used for carburizing are Methanol and Isopropyl acetone. Methanol acts as carrier gas and isopropyl acetone is responsible for liberation of carbon free radicals. Controlling gas atmospheres controls the carbon potential inside the furnace. The carbon potential inside the furnace is measured by using OXY-PROBE.

To obtain the required conditions, the temperature inside the furnace is maintained at 910°C, and the millivolt generated is 1113mV. The carburizing time is one and half an hour. After the required conditions are reached, the charge is soaked for diffusion of carbon particles for half an hour, and soaking temperature is maintained at 820°C.

In the component under consideration, the case hardness required is between 79 to 82 HRA to a case depth between 0.65 to 0.85 mm.

Quenching

The charge is transferred from the furnace into quenching tank quickly. Oil is used as quenchant, which is maintained at a temperature of 30°C.

Tempering

To aid for subsequent operations and to improve certain mechanical properties tempering is done. The temperature of the tempering furnace is maintained at 150°C for one hour.

Objectives of the Experimentation

❖To get the required case depth and surface hardness value with acceptable level of distortion (i.e. bend & unwind of helix angle) in pinion.

❖To identify the values of the controlling factors

The major contributing factors are identified from the list mentioned above and their levels are defined in the table 1.

Interactions

❖Furnace Temperature Vs Quenching Time (AXB)

❖Furnace Temperature Vs Tempering Temperature (AXC)

The case depth and hardness of all the samples are found to be consistent and well within the limits as before the experiment. The hardness values obtained for the samples are plotted in the Figure 1

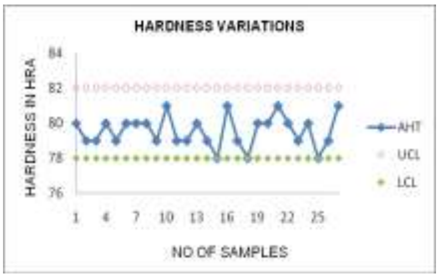


Figure -1 shows the HARDNESS in HRA

Measurement of Size distortion

The size distortion of the gas carburized (pinion component) are measured using mechanical dial gage (Runout variation) and gear tester (helix variation) and are given in Figure 2,3and 4.

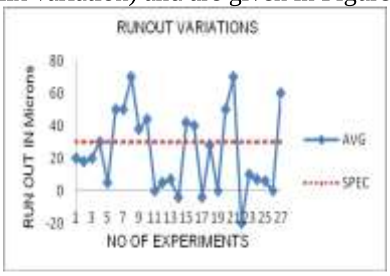


Figure-2 shows the Runout in microns

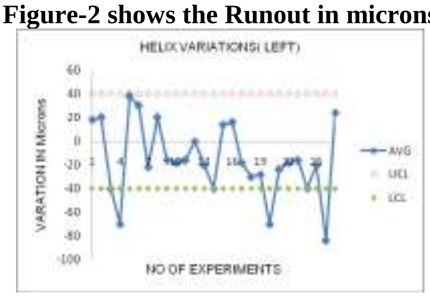


Figure -3 shows the Helix variations (Left) in microns

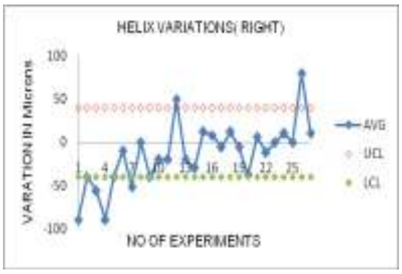


Figure -4 shows the Helix variations (Right) in microns

Optimization by Response Graph

Runout

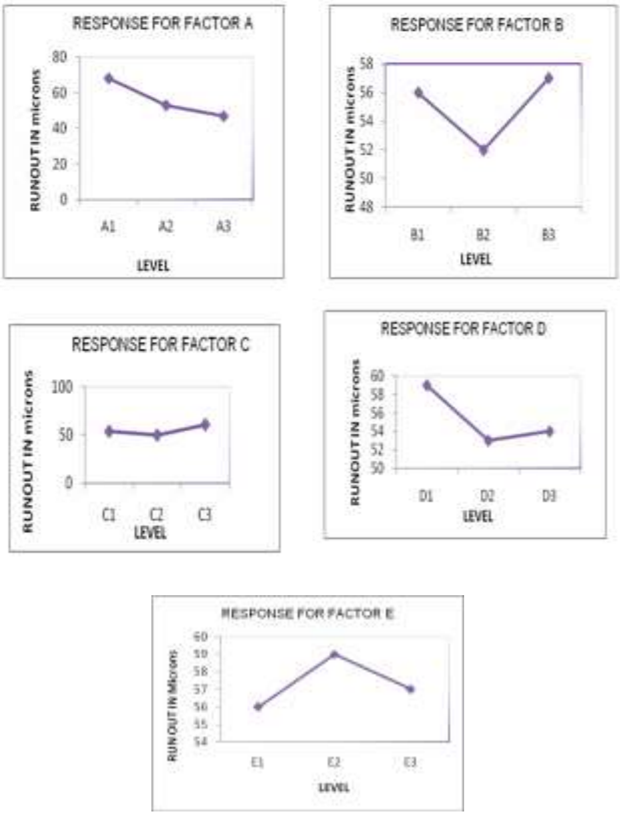


Figure- 5 shows the Response graphs for individual factors.

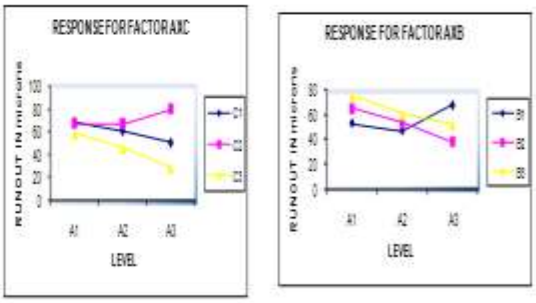
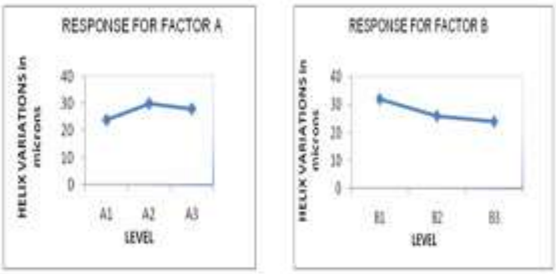


Figure -6 shows the Response graphs for interactions

HELIX:



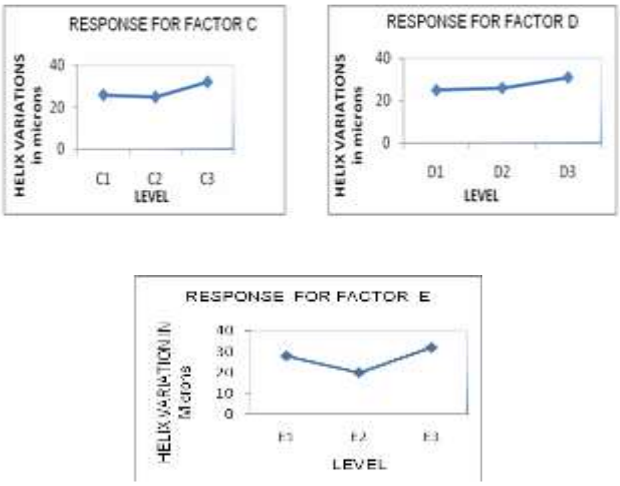


Figure- 7 shows the Response graphs for individual factors

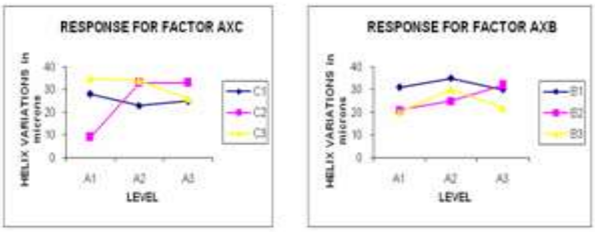


Figure- 8 shows the Response graphs for interactions

The optimum combinations of factors are obtained from the response graphs shown in figures 5, 6, 7, and 8 and the result is shown in table 5.

S/N Ratio Method (Signal to Noise)

S/N ratio measures the sensitivity of the quality characteristic being investigated in a controlled manner, to those external influencing factors not under control. The high value of S/N ratio implies that the signal is much higher than the random effect of the noise factor.

The required QC for runout is "smaller the best", S/N ratio $= -10 \log (MSD)$

$MSD = [\sum (Y_i)^2] / N$

The required QC for helix variation is "Nominal the better", S/N ratio $= -10 \log(MSD)$

$MSD = \sum (Y_i - M)^2/N$

Where M = Allowable deviations (40 microns), N = No. of trials

Optimum combination:

Table 6 shows the S/N ratio for Runout and helix variations and it indicates that the maximum S/N value is obtained in the 23rd row and 8th of OA. The corresponding factor level confirms the results of RG method.

Predicted mean response:

Using the Taguchi method for parameter design, the predicted mean response for the combined optimum combination is calculated and this is characterized by the following equation.

$$\beta = T + (A_{opt} - T) + (B_{opt} - T) + (C_{opt} - T) + (D_{opt} - T) + (E_{opt} - T)$$

Where, β= predicted mean response, T= mean of all observations in the data.

For Runout, $\beta_r = T + (A_3 - T) + (B_2 - T) + (C_2 - T) + (D_2 - T) + (E_2 - T) = 24.99$ microns

=25 microns (approx.)

For Helix, $\beta_H = T + (A_1 - T) + (B_3 - T) + (C_2 - T) + (D_1 - T) + (E_2 - T) = 9.927$ microns

=10 microns (approx.)

Experiments were conducted at the optimum combination level as found out from the experimentation to find out extent of run out and helix variations. The results are shown in the tables 8 and 9 and it is clear that the values are within the specified limits.

Combined Optimum Condition

The combined optimum combination is obtained by considering both the run out and helix optimum combinations.

Predicted mean response:

The predicted mean response for the combined optimum combination is calculated by considering the corresponding factor levels.

$$\beta = T + (A_{opt} - T) + (B_{opt} - T) + (C_{opt} - T) + (D_{opt} - T) + (E_{opt} - T)$$

Where, β= predicted mean response, T= mean of all observations in the data.

β_R =25 microns and β_H =17 microns

Time saving:

In optimum condition, the furnace temperature is kept at 940ºC, instead of usual 910ºC. The furnace will take an additional half an hour to reach this temperature on loading. Quenching time is increased from 30 minutes to 60 minutes. Tempering time is increased from 60 minutes to 120 minutes.

Increase in time of production per loading in optimum condition = 120 minutes

Time for straightening per pinion = 1.5 minutes

Time of straightening per loading = 1.5 X 300

= 450 minutes

Time saved per loading = 5.5 hours

Due to reduced lead-time and production cost, production rate is increased and unit cost of pinion is reduced.

Conclusions

The experimental investigations have shown that in Gas carburizing process under optimal conditions surface integrity is good and undesired effects associated with metallurgical and thermal aspects are also minimal.

Under optimum parameters combination, it is observed that the run out in pinion is within 30 microns and unwind of helix angle is within 40 microns. Since the distortion after heat treatment is controlled within the tolerance limit, the straightening operation, which is done after tempering, is eliminated and productivity is also considerably improved.

Future scope:

One of the important parameters, that plays a major role in distortion is quenching. During quenching, austenite transforms into martensite. When the quenching temperature is low, it favors martensite formation. To aid martensite formation and transformation of retained austenite (which causes distortion) into martensite, it is advisable to go for SUB ZERO QUENCHING.

One of the factors that influence the distortion during heat treatment is holding position of the component inside the furnace. Vertical holding position yields minimum distortion. To ensure vertical position through out the process, SCREWED TYPE FIXTURE can be used.

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Table-1 shows the Factors and levels

SL. NO.	Factors	Level 1	Level 2	Level 3
1	Furnace temperature (A)	870°C	910°C	940°C
2	Quenching Time (B)	30min	60min	90 min
3	Tempering Temperature(C)	150°C	200°C	250°C
4	Tempering Time (D)	90 min	120 min	150 min
5	Preheating (E)	Yes (150°C)	No	-

Table- 2 shows the Optimum Combinations for Run out and Helix

S.No	Factors	Levels		Description	
		Runout	Helix	Runout	Helix
1	Furnace temperature	A3	A1	940 ºC	840 ºC
2	Quenching time	B2	B3	60 min.	90 min.
3	Tempering temperature	C2	C2	200 ºC	200 ºC
4	Tempering time	D2	D1	120 min.	90 min.
5	Preheating	E2	E2	No preheating	No preheating

Table- 3 shows the S/N Ratio for Runout and helix variations methods

Sl. No.	Runout in microns		S/N values for Runout	Helix variations in microns		S/N values for Helix
	Trial 1	Trial 2		Trial 1	Trial 2	
1	0.03	0.03	30.45	2.8	39.8	-28.4
2	0.00	0.03	33.47	12.9	14.9	-28.339
3	0.04	0.00	30.96	64.3	50.1	-25.39
4	0.02	0.08	24.69	0.4	51.5	29.295
5	0.01	0.02	36.02	11.8	10.3	29.235
6	0.07	0.03	25.38	14.4	36.8	25.22
7	0.06	0.04	25.85	44.0	28.2	18.89
8	0.04	0.10	22.37	3.1	0.1	31.693
9	0.01	0.02	36.02	26.1	20.9	24.456
10	0.00	0.00	0.00	43.4	6.3	27.586
11	0.10	0.05	23.01	74.0	74.0	30.88
12	0.09	0.05	22.75	42.0	0.00	19.04
13	0.02	0.02	33.98	11.7	13.5	28.75
14	0.00	0.03	33.47	46.3	33.6	16.055
15	0.00	0.03	33.47	14.1	33.7	25.505
16	0.01	0.01	40.00	26.9	34.3	20.088
17	0.00	0.00	0.00	0.7	41.5	28.88
18	0.07	0.05	24.32	40.7	34.4	12.02
19	0.06	0.03	26.48	12.7	31.4	26.12
20	0.01	0.01	40.48	26.9	47.1	20.453
21	0.02	0.00	36.99	47.0	15.2	25.21
22	0.03	0.06	26.48	43.9	35.2	12.816
23	0.01	0.00	43.01	6.4	26.8	28.139
24	0.02	0.07	25.77	52.1	25.2	22.617
25	0.03	0.05	27.69	0.9	23.5	29.544
26	0.00	0.03	33.47	38.2	51.0	17.932
27	0.04	0.01	30.71	1.6	15.3	30.18

Table- 4 Optimum combination for Runout and helix variations methods

Sl.No.	Optimum combination for run out and helix variations			
	S/N ratio		RG method	
	Runout	Helix variations	Runout	Helix variations
1	A3	A1	A3	A1
2	B2	B3	B2	B3
3	C2	C2	C2	C2
4	D3	D1	D2	D1
5	E2	E2	E2	E2

Table- 5 shows the Confirmation Trial for Runout and helix variations

Sample Nos.	Runout in microns	Helix variations in microns
1	20	4.6
2	24	10.4
3	30	-5.3
4	26	-6.1
5	20	-12.7
6	25	8.9
7	23	-1.6
8	27	-1.3
9	30	11.06
10	28	-8.11

Table- 6 shows the Combined Optimum combination

SL.NO.	FACTOR	LEVEL	DESCRIPTION
1	Furnace Temperature	A3	940°C
2	Quenching Time	B2	90 min
3	Tempering Temperature	C2	200° C
4	Tempering Time	D2	120 min
5	Preheating	E2	NO

Table -7 shows the Confirmation Trial for combined optimum combination

Samples nos.	RUNOUT in microns	HELIX in microns
1	30	-10.6
2	27	-11.05
3	10	-20.11
4	23	5.0
5	28	18.46
6	30	-13.12
7	20	17.85
8	15	-15.0
9	25	-18.15
10	28	21.22