Diffraction Notes

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EFFICIENTLY OPTIMIZING MANUFACTURING PROCESSES USING ITERATIVE TAGUCHI ANALYSIS

INTRODUCTION

Taguchi experimental methods are now widely used in many industries to efficiently optimize the manufacturing process. An iterative approach allows multiple complex properties to be rapidly optimized at minimal cost.

Taguchi design of experiment (DOE) methods incorporate orthogonal arrays to minimize the number of experiments required to determine the effect of process parameters upon performance characteristics. The Taguchi experimental approach allows a statistically sound experiment to be completed while investigating a minimum number of possible combinations of parameters or factors. A Taguchi experiment can be accomplished in a timely manner and at a reduced cost with results comparable to a full factorial experiment.

Lambda Research offers studies designed to optimize properties such as residual stress, retained austenite, phase composition, texture and cold working measurable by x-ray diffraction based upon Taguchi techniques. Minimizing tensile residual stresses in machining and grinding and optimizing the depth and magnitude of compression in shot peening while maintaining cold work are typical process optimization studies amenable to Taguchi methods. The following *Diffraction Notes* article describes the application of Taguchi DOE methods to optimize the heat treatment of a bearing steel. Our engineering staff would be pleased to discuss application of Taguchi methods for the optimization of other manufacturing processes.

EXPERIMENTAL DESIGN AND TECHNIQUE

The objective of this study was to determine a procedure for the heat treatment of 52100 steel yielding simultaneously the highest hardness and the lowest level of retained austenite employing a Taguchi experimental design. The factors identified as affecting the retained austenite and/or hardness were austenitizing temperature, tempering temperature, tempering time, and cold treatment.[3,4]

To identify any interactions that may take place among the factors, an L16 $(2)^{15}$ array, with two levels for each factor, was chosen for the initial experiment (DOE A). The recommended heat treatment[4] commonly performed for 52100 steel was the basis for selection of the initial two levels for each factor. The L16 $(2)^{15}$ designation refers to the number of experiments (16), the number of levels for each factor (2), and the number of factors or interactions (15).

Once the possible interactions were identified an L9 $(3)^4$ array, employing nine experiments, three levels for each of the remaining four factors or interactions, was chosen for a second analysis (DOE B). Finally, a third Taguchi experiment (DOE C) was performed to refine the results of the second experiment and approach the optimal heat treating parameters. The retained austenite measurements were made in

ANNOUNCEMENTS

Website Update

All of our publications are now available for direct download from our website**, www.lambda-research.com**. We recently included the abstracts under the title to enable you to search for publications of interest.

Low Plasticity Burnishing

Lambda Research was recently awarded a patent for low plasticity burnishing (LPB). The apparatus and process were developed to provide a practical, cost effective means of surface enhancement. This technology is capable of producing deep thermally stable compression in local high stress areas of fatigue critical parts. Preliminary results will be presented at the 5th National Turbine Engine High Cycle Fatigue Conference in Chandler, Arizona, March 7-9, 2000. Watch our website for future updates and developments.

accordance with ASTM E975 and SAE SP-453, using the direct comparison method of Averbach and Cohen.[5] The unit cell volume and the chemical composition of 52100 steel were used to calculate the intensity factors, "R".[6]

The integrated intensity of each austenite and ferrite/martensite peak was measured using chromium K-alpha radiation. The use of multiple diffraction peaks from each phase minimizes the possible effects of preferred orientation and coarse grain size. Four independent volume percent retained austenite values were calculated from the integrated intensities of the austenite (200) and (220) and ferrite/martensite (200) and (211) diffraction peaks.

A Miller fixture [7] was used to minimize the influence of preferred orientation and grain size. The Miller fixture rotates the specimen around the surface normal and oscillates (± 45 deg.) perpendicular to the diffraction plane.

The factors and levels selected for DOE A analysis are shown in Table I. A full factorial matrix was selected for the initial experiment to identify all possible interactions between the main factors. Once the interactions between the factors are established for any process, heat treating in this instance, the larger matrix need not be repeated for further refinement of the same process.

	Factors	Level 1	Level 2
A	Austenizing Temperature	774 C (1425 F)	871 C (1600 F)
B	Tempering Temperature	93 C (200 F)	343 C (650 F)
D	Temper Time	1 Hr.	4 Hrs.
H	Cold Treatment	None	1 Hr.
	Interactions		
C	Aust. Temp. vs Temper Temp.	--	--
E	Aust. Temp. vs. Temper Time	--	--
F	Temper Temp. vs. Temper Time	--	--
I	Aust. Temp. vs. Cold Treat.	--	--
J	Temper. Temp. vs. Cold Treat.	--	--
L	Temper Time vs. Cold Treat.	--	--

Table I Factor & Level Descriptions for Taguchi DOE A

The factors and levels for DOE B are shown in Table II. Three levels were selected for each factor so that any trends in the data would be more readily detected.

	Factors	Level 1	Level 2	Level 3
A	Austenizing Temperature	774 C (1425 F)	827 C (1520 F)	871 C (1600 F)
B	Tempering Temperature	93 C (200 F)	177 C (350 F)	343 C (650 F)
C	Temper Time	1 Hour	2 Hours	4 Hours
D	Cold Treatment	None	0.5 Hour	1 Hour

Table II Factor & Level Descriptions for Taguchi DOE B

The factors and levels for DOE C are shown in Table III. The levels for the third experiment were selected based upon the results of the second experiment to further refine the heat treatment procedure. The range of the factors between Level 1 and Level 3 was decreased for the third experiment.

	Factors	Level 1	Level 2	Level 3
A	Austenizing Temperature	774 C (1425 F)	802 C (1475 F)	827 C (1520 F)
B	Tempering Temperature	93 C (200 F)	135 C (275 F)	177 C (350 F)
C	Tempering Time	1 Hour	1.5 Hours	2 Hours
D	Cold Treatment	None	0.25 Hour	0.5 Hour

Table III Factors & Level Descriptions for Taguchi DOE C

The factors assigned to an L9 $(3)^4$ orthogonal array for the second and third experiments as shown in Tables IV and V, respectively. The nine experiments for each DOE were then randomized within each group.

	$L_9 (3)^4$				A(a)	B(b)	C	D(d)
Factors	A	B	C	D	Aust.	Temper	Temper	Cold
Exp.	1	2	3	4	Temp.	Temp.	Time	Treat.
1	1	1	1	1	774 C (1425 F)	932 C (700 F)	1 Hr.	None
2	1	2	2	2	774 C (1425 F)	177 C (350 F)	2 Hrs.	0-5 Hr.
3	1	3	3	3	774 C (1425 F)	343 C (650 F)	4 Hrs.	1 Hr.
4	2	1	2	3	827 C (1520 F)	936 C (200 F)	2 Hrs.	1 Hr.
5	2	2	3	1	827 C (1520 F)	177 C (350 F)	4 Hrs.	None
6	2	3	1	2	827 C (1520 F)	343 C (650 F)	1 Hr.	0.5 Hr.
7	3	1	3	2	871 C (1600 F)	93 C (200 F)	4 Hrs.	0.5 Hr.
8	3	2	1	3	871 C (1600 F)	177 C (350 F)	1 Hr.	1 Hr.
9	3	3	2	1	871 C (1600 F)	343 C (650 F)	2 Hrs.	None

Table IV $L_9 (3)^4$ Array for Taguchi DOE B.

	$L_9 (3)^4$				A	B	C	D
Factors	A	B	C	D	Austenizing	Tempering	Temper	Cold
Exp.	1	2	3	4	Temperature	Temperature	Time	Treat.
1	1	1	1	1	774 C (1425 F)	932 C (200 F)	1 Hr.	None
2	1	2	2	2	774 C (1425 F)	135 C (275 F)	1.5 Hrs.	0.25 Hrs.
3	1	3	3	3	774 C (1425 F)	177 C (350 F)	2 Hrs.	0.5 Hr.
4	2	1	2	3	802 C (1475 F)	135 C (275 F)	1.5 Hrs.	0.5 Hr.
5	2	2	3	1	802 C (1475 F)	135 C (275 F)	2 Hrs.	None
6	2	3	1	2	802 C (1475 F)	177 C (350 F)	1 Hr.	0.25 Hr.
7	3	1	3	2	827 C (1520 F)	93 C (200 F)	2 Hrs.	0.25 Hrs.
8	3	2	1	3	827 C (1520 F)`	135 C (275 F)	1 Hr.	0.5 Hr.
9	3	3	2	1	827 C (1520 F)	177 C (350 F)	1.5 Hrs.	None

Table V $L_9(3)^4$ Array for Taguchi DOE C.

RESULTS AND DISCUSSION

The results obtained for the first, second, and third experiments are shown in Tables VI, VII, and VIII, respectively

The response data are plotted in Figures 1 and 2 for DOE A. The results indicate that the tempering temperature and the cold treatment have the most influence, and the austenitizing temperature and tempering time have the least influence on the retained austenite levels. The tempering temperature and the austenitizing temperature appear to have the most influence on the hardness, with the cold treatment and temper time having some influence. The tempering time and cold treatment seem to be interacting in relation to the retained austenite levels. None of the main factors show strong interactions in relation to the hardness.

The results of the first experiment (DOE A) indicate a lower austenite content at the higher tempering temperature of 343C and after the one hour cold treatment. The hardness also seems to be most influenced by the tempering temperature followed by the austenitizing temperature. Hardness is highest at the lower tempering temperature of 93C and at the higher austenitizing temperature of 871C. The cold treatment (none and one hour) and tempering time (one hour and four hours) appear to have a minimal affect on the hardness. There is an interaction between the cold treatment and the tempering temperature in relation to the retained austenite.

Experiment	Volume Percent Retained Austenite	Hardness (Rockwell C Scale)
A-1	6.4	59.1
A-2	2.8	60.4
A-3	7.9	52.9
A-4	2.1	53.9
A-5	0.2	39.9
A-6	0.1	47.8
A-7	0.1	38.9
A-8	0.1	42.8
A-9	5.9	61.8
A-10	2.2	62.7
A-11	7.2	61.0
A-12	1.0	62.1
A-13	0	50.6
A-14	0	52.7
A-15	0	50.2
A-16	0	51.3

Table VI Experimental Results for DOE A.

Experiment	Volume Percent Retained Austenite	Hardness (Rockwell C Scale)
B-1	15.0	61.1
B-2	0	56.6
B-3	0	47.9
B-4	6.1	65.4
B-5	0	58.9
B-6	0.1	55.1
B-7	10.2	66.7
B-8	0	60.9
B-9	0	53.2

Table VII Experimental Results for DOE B.

Experiment	Volume Percent Retained Austenite	Hardness (Rockwell C Scale)
C-1	11.5	59.5
C-2	2.4	43.5
C-3	0	54.0
C-4	4.5	62.3
C-5	13.4	59.3
C-6	0	58.1
C-7	6.7	65.0
C-8	4.5	62.4
C-9	0	58.7

Table VIII Experimental Results for DOE C.

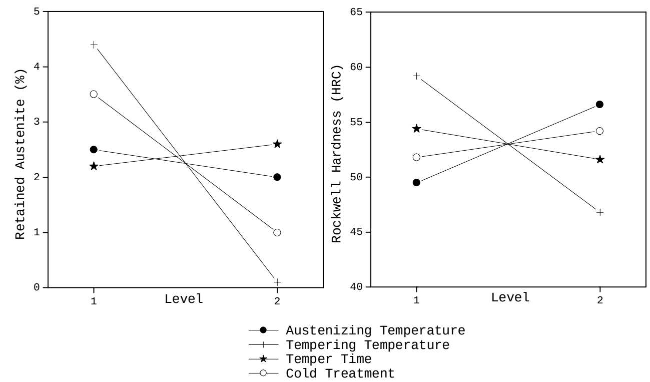

Fig. 1 Plot of Response Data for Main Factors of DOE A.

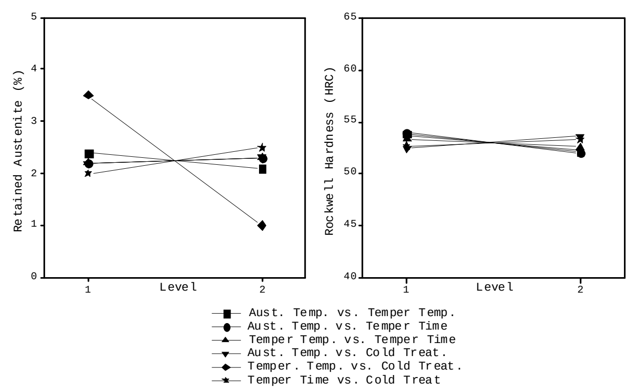

Fig. 2 Plot of Response Data for Interactions of DOE A.

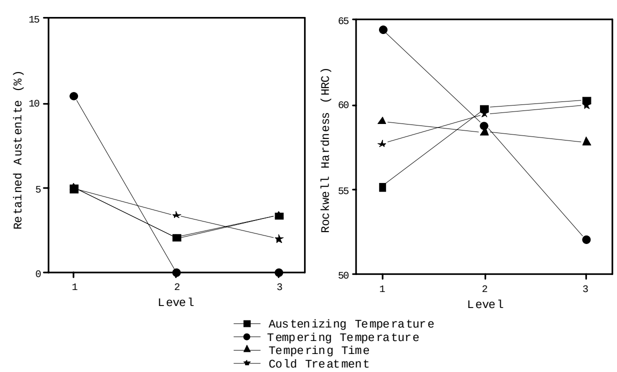

Fig. 3 Plot of Response Data for Main Factors of DOE B.

The response data are plotted in Figure 3 for the second experiment, DOE B. As expected, the data indicate a high austenite content and a high hardness for the lowest tempering temperature and low austenite content and low hardness for the highest tempering temperature.

The results obtained in DOE B indicate the factor most influencing the retained austenite and hardness is the tempering temperature.

The response data for the third more refined experiment DOE C are plotted in Figure 4. These results also indicate that the lowest austenite content is associated with the highest tempering temperature. The hardness appears to increase in magnitude from Level 1 to Level 3 as the austenitizing temperature is increased from 774C to 827C.

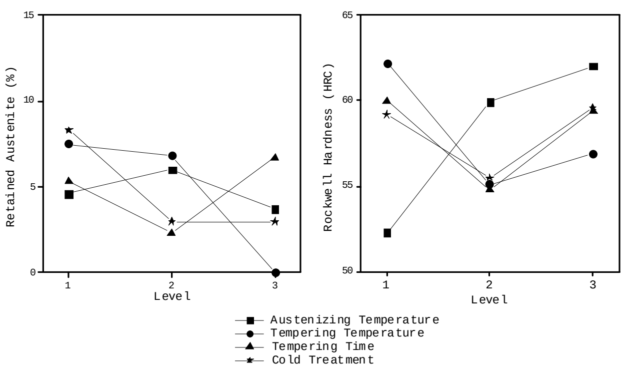

Fig. 4 Plot of Response Data for Main Factors of DOE C.

Conditions		
Factors	Condition 1	Condition 2
Austenizing Temperature	827 C (1520 F)	827 C (1520 F)
Tempering Temperature	177 C (350 F)	177 C (350 F)
Tempering Time	2 Hrs.	2 Hrs.
Cold Treatment	1 Hr.	None
Results		
Volume Percent Retained Austenite	0	0
Hardness Rockwell C	58.7	57.9

Table IX Experimental Confirmation

The "optimum" conditions that gave the lowest austenite content and the highest hardness are shown in Table IX. The results appear to indicate that the cold treatment might have an effect on the hardness of the 52100 steel, but this cannot be confirmed because of the interaction that takes place with the tempering temperature and cold treatment shown in the interactions for DOE A. Therefore, dual confirmation experiments were performed with only one sample cold treated. The confirmation experiment was successful, resulting in no detectable retained austenite and a hardness value on the order of 58 HRC for both samples.

The confirmation results do not support the hypothesis that cold treatment may increase the hardness. The confirmation experiment also indicates that although an interaction exists between the tempering temperature and the cold treatment, the tempering temperature has the most influence on the retained austenite content.

CONCLUSIONS

The experiments conducted show that austenitizing and tempering temperatures have the most influence on the retained austenite and the hardness in the heat treatment of 52100 steel. The austenitizing and tempering temperatures of 827C and 177C, respectively, gave the lowest austenite and highest hardness values for both the second and final Taguchi analyses, indicating that no further refinement of the experiment is necessary. Therefore, if the goal of heat treating 52100 steel is to produce the lowest austenite content and the highest hardness, either condition 1 or 2, shown in Table IX, could be used. The experiment also indicates that to produce the best product (low austenite content and high hardness) the process controls should be placed on the austenitizing temperature and the tempering temperature.

This study is intended to illustrate the use of Taguchi DOE methods employing x-ray diffraction retained austenite measurement to efficiently develop heat-treatment parameters for steels. It is not intended to provide optimal parameters for any specific application of 52100 steel. The final heat treatment selected to produce negligible austenite and 58 HRC material is not intended to be optimal for any particular application. However, the same experimental approach can, in principle, be used to efficiently develop any achievable set of properties in the heat treatment of steels.

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