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Optimization of Case Treatment AISI 1022 Timber Screw Process Parameters Using Taguchi Method

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The manufacturing processes of timber screws, which are widely used for wood construction work, include wire manufacturing, heading and threading, case treatment, and coating. A low-carbon steel wire of AISI 1022 is used to easily fabricate timber screws. The majority of case treatment activities are performed to improve the screw strength without affecting the soft, tough interior of the screws in drilling operation. In this study, the Taguchi method is used to obtain optimum case treatment conditions to improve the mechanical properties of AISI 1022 timber screws. The quality of case-treated timber screws is affected by various factors, such as case treatment temperature, case treatment time, atmosphere composition, and tempering temperature. The effects of case treatment parameters affect the quality characteristics, such as case hardness and torsional strength. It is experimentally revealed that ammonia flow rate, case treatment time, and carbon potential are significant for case hardness, while methanol flow rate, case treatment temperature, and case treatment time are significant for torsional strength. The optimum mean case hardness is 673.1 HV, the optimum mean core hardness is 440.0 HV and, for torsional strength, the optimum mean value is 5.3 N·m. The new case treatment parameter settings evidently improve the performance. The strength of the case-treated AISI 1022 timber screws is effectively improved. These results may be used as a reference for fastener manufacturers.

1. Introduction

The manufacturing processes of timber screws, which are widely used for construction work, include wire manufacturing, forming, heat treatment, and coating. To readily fabricate timber screws, low-carbon steel wires are usually used. To increase the strength of screws in self-drilling operation, case hardening treatment is usually an essential process that is used to improve the wear resistance and not affect the soft, tough interior of the screws. This combination of a hard surface and resistance to breakage is valuable in the manufacture of timber screws, which have a hard surface to resist wear, along with a tough interior to resist the breakage that occurs during self-drilling operation.

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Gas carburization is a case hardening process in which carbon is dissolved in the surface layers of a low-carbon steel part at a temperature sufficient to make the steel austenitic, followed by quenching and tempering to form a martensitic microstructure.[1] Various principal variables, such as temperature, time, and atmosphere composition, affect the quality of gas carburization. Goldstein and Moren[2] had developed mathematical models for simulating the carburization process. One model simulates carburization in low-alloy steels by varying the temperature, time, surface carbon content, and diffusion coefficient during the process. Experimental data for carburization treatments of Fe–C–Cr alloys were in excellent agreement with model predictions of major increases in effective surface carbon content and the formation of carbides in austenite at the carburization temperature.

The carburization temperature varies from 870 to 940 °C and the gas atmosphere for carburization is produced from a liquid or gaseous hydrocarbon such as propane, butane or methane.[3] The process converts the outer layer of a screw into a high-carbon steel with a carbon content in the range of 0.9–1.2%. Effective case depth is an important factor and goal in gas carburization, involving complicated procedures in the furnace and requiring precise control of many thermal parameters.[4] The effective case depth governed by carburization temperature, time, the carbon content of steel, and the carbon potential of atmosphere is calculated, and a simple and practical set of guidelines for optimizing gas carburization has been provided for plant production. Aramide *et al.*[5] studied the effects of the carburization temperature and time on the mechanical properties of mild steels carburized with activated carbon, and observed that the mechanical properties of mild steels were strongly affected by the process of carburization, carburization temperature, and soaking time at the carburization temperature. They concluded that the optimum combination of mechanical properties is achieved at the carburization temperature of 900 °C followed by oil quenching and tempering at 550 °C. Peng *et al.*[6] studied the carburizing behaviors and mechanisms of Cr35Ni45Nb alloy subjected to different service conditions in a high-temperature vacuum environment. Ivanov *et al.*[7] studied carburization and different heat treatments of low-carbon martensitic steel 24Kh2G2NMFB and suggested heat treatment modes to improve the structure of the surface layer after carburization.

Carbonitridation, a modified form of gas carburization, induced by diffusing both carbon and nitrogen into the surface layer enables the process to be carried out at a lower temperature and a shorter time than with carbon alone. Carbonitridation is used primarily to impart a hard, wear-resistant case. The case depth depends on the time and temperature of treatment. Carbonitridation is an excellent choice for low-carbon fastener materials that require a uniform but shallow case with good wear properties.[8] Besides the process temperature, the combined diffusion profile of carbon and nitrogen applied in carbonitridation plays a major role. Winter[9] presented a new system that enables us to measure and control both the carbon potential and the nitrogen potential independently. Slycke and Ericsson[10] have studied theoretically and experimentally the reactions occurring during carbonitridation. Semenova *et al.*[11] considered the regular features of the formed diffusion layers in the temperature-cycle carbonitridation of steel 20 Kh and used the solution of the general diffusion problem to determine the diffusivity of carbon. Karamiş and İpek[12] investigated the wear behavior of carburized and carbonitrided AISI 1020 and 5115 steels. The carbonitrided 5115 steel has the highest wear resistance followed by the carburized 5115, carbonitrided 1020, and carburized 1020 steels. Fares *et al.*(13) investigated gaseous carbonitriding effects on the improvement of the surface characteristics of a new hot working tool steel close to either chromium AISI H11 or AISI H13. The microstructure and diffusion mechanism suggested that high-temperature gas carbonitridation has the potential to improve the mechanical properties of steels with shorter processing time.

In this study, in order to obtain the optimum case treatment quality of AISI 1022 timber screws, a series of case treatment experiments is conducted in a continuous furnace. Various parameters, such as quenching temperature, case treatment time, atmosphere composition (carbon potential and ammonia level), and tempering temperature, affect the case treatment quality. The effects of treatment parameters on the quality characteristics of timber screws, such as case hardness, core hardness, and torsional strength, are analyzed by using the Taguchi method.

2. Experimental Design

Carburization and Carbonitridation are often used to achieve deeper case depths and higher engineering performance for timber screws. A series of case treatment experiments on AISI 1022 timber screws is conducted in a continuous furnace and then the screws are oil-quenched and tempered at 230 °C for 45 min.

To evaluate the mechanical properties of the timber screws, seven controllable process factors are identified: 1 at two levels and 6 at three levels. All factors and their levels are shown in Table 1. The parameters of Level 2 are the original case treatment conditions, which were used in the company.

The Taguchi method allows simultaneous changes of many factors in a systematic manner, ensuring the reliable and independent study of the factors' effects. The orthogonal array table, $L_{18}(2^1 \times 3^7)$,(14,15) is used as an experimental design for these seven factors, as shown in Table 2.

In this study, two quality characteristics of the case-treated timber screws, namely, case hardness (as measured in Fig. 1) and torsional strength, are investigated. Each test trial, including nine specimens, is followed by a fabrication process and the results are then transformed to the signal-to-noise (S/N) ratio. For a nontreated screw, the case hardness of 208.3 HV is measured on the tooth and the core hardness of 173.0 HV is tested at the center of the screw, as shown in Fig. 1. Since the hardness of the workpiece may be increased by plastic

Table 1
Experimental factors and their levels for L_{18} orthogonal array.

	Factor	Level 1	Level 2	Level 3
A:	Flow rate of ammonia (NH_3) (L/min)	0.5	0.0*	
B:	Flow rate of methanol (CH_3OH) (L/min)	1.0	1.5	2.0
C:	Feeding weight (kg/h)	600	700	800
D:	Case treating temperature (°C)	860	880	900
E:	Case treating time (min)	40	50	60
F:	Carbon potential (%)	0.9	1.0	1.1
G:	Quenchant temperature (°C)	80	85	90

*Without ammonia (0.0 L/min) for carburization.

Table 2
$L_{18}(2^1 \times 3^7)$ orthogonal array experimental parameter assignment.

Exp. No.	A: Flow rate of ammonia (NH_3) (L/min)	B: Flow rate of methanol (CH_3OH) (L/min)	C: Feeding weight (kg/h)	D: Case treating temperature (°C)	E: Case treating time (min)	F: Carbon potential (%)	G: Quenchant temperature (°C)
L1	0.5	1.0	600	860	40	0.9	80
L2	0.5	1.0	700	880	50	1.0	85
L3	0.5	1.0	800	900	60	1.1	90
L4	0.5	1.5	600	860	50	1.0	90
L5	0.5	1.5	700	880	60	1.1	80
L6	0.5	1.5	800	900	40	0.9	85
L7	0.5	2.0	600	880	40	1.1	85
L8	0.5	2.0	700	900	50	0.9	90
L9	0.5	2.0	800	860	60	1.0	80
L10	0.0	1.0	600	900	60	1.0	85
L11	0.0	1.0	700	860	40	1.1	90
L12	0.0	1.0	800	880	50	0.9	80
L13	0.0	1.5	600	880	60	0.9	90
L14	0.0	1.5	700	900	40	1.0	80
L15	0.0	1.5	800	860	50	1.1	85
L16	0.0	2.0	600	900	50	1.1	80
L17	0.0	2.0	700	860	60	0.9	85
L18	0.0	2.0	800	880	40	1.0	90

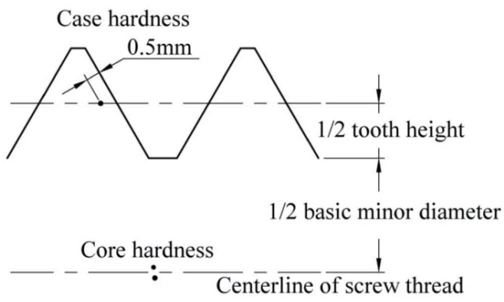

Fig. 1. Schematic illustration of measuring case hardness and core hardness.

flow,[16] the case hardness is greater than the core hardness mainly owing to the plastic work of threading. The torsional strength is only 2.83 N·m.

Through case treatment, the strength of timber screws may be improved, and the case hardness, which is the main quality characteristic obtained from the Vickers hardness test, and torsional strength (drilling performance) may be increased as well. Both quality characteristics are with nominal values of 600 HV case hardness and 4.5 N·m torsional strength, assigned by the company. Therefore, in terms of the desired characteristics for the case hardness and torsional strength, the S/N ratio for the nominal-the-best response is[15]

$$S/N = -10 \cdot \log[(\mu - m)^2 + S^2], \tag{1}$$

where μ is the mean of each trial, m is the target value, and S is the standard deviation.

The analysis of variance (ANOVA) is an effective method of determining the significant factors and optimal fabrication conditions to obtain the optimal quality. In the Taguchi method, the experimental error is evaluated by ANOVA to carry out the significance test of the various factors. The nature of the interaction between factors is considered as experimental error.(15) If the effect of a factor in comparison with the experimental error is sufficiently large, it is identified as a significant factor. The confidence level of a factor is evaluated with the experimental error to identify the significant factor that affects the material properties of the timber screws.

3. Materials and Methods

In this study, the AISI 1022 steel wire coil is manufactured by TYCOONS Worldwide Group (Thailand) Public Co., Ltd. Its chemical composition is shown in Table 3. A series of case treatment experiments on AISI 1022 timber screws (#8×2-1/2 CS) is conducted in a CCF-CF-7-E continuous furnace (Chuang Young Enterprise Co., Ltd., Yunlin, Taiwan), and then the screws are oil-quenched and tempered at 230 °C for 45 min. The case treatment procedure is shown in Fig. 2. The Taguchi method allows simultaneous changes of many factors in a systematic manner. The orthogonal array table, $L_{18}(2^1 \times 3^7)$, is used as an experimental design for the factors,(15) as shown in Table 2.

4. Results and Discussion

Case treatment is the process of diffusing carbon and/or nitrogen into the surface layer, as shown in Fig. 3, to impart a hard, wear-resistant case. Compared with the measures of nontreated screws, the core hardness and case hardness increase together, although the

Table 3
Chemical composition of AISI 1022 low-carbon steel wires (wt%).

C	Mn	P	S	Si	Al
0.18–0.23	0.74–0.84	0.009–0.025	0.007–0.014	0.04–0.06	0.028–0.053

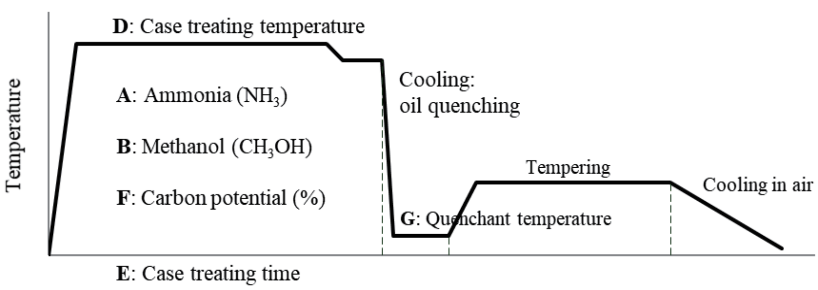

Fig. 2. Case treating procedure.

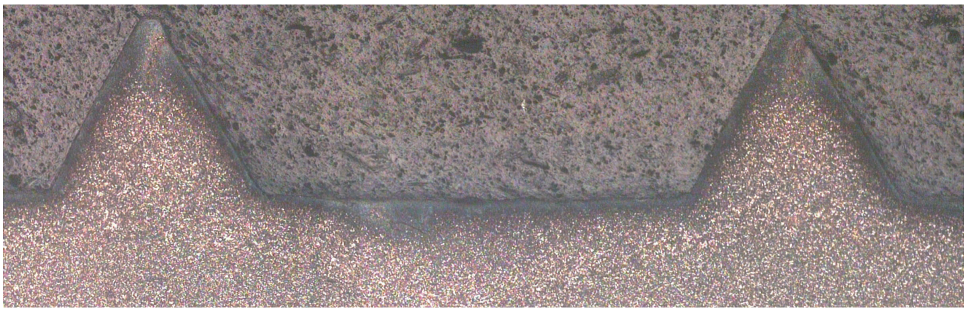

Fig. 3. (Color online) Microstructure of timber screw (×200).

increment of case hardness (more than 450 HV) is much higher than that of core hardness (less than 300 HV); the torsional strength also increases.

When the screws are fabricated following the original case treatment conditions (Level 2 in Table 1), the mean torsional strength, case hardness, and core hardness are 6.56 N·m, 660.3 HV, and 460.6 HV, respectively. The experimental results of the torsional strength, case hardness, and core hardness (mean, μ; standard deviation, S; and S/N ratio) of case-treated timber screws are respectively shown in Tables 4, 5, and 6.

As shown in Table 4, the mean torsional strengths of all tests are larger than the target value of 4.5 N·m. The standard deviation varies from 0.082 to 0.188 N·m and tests L5, L6, and L7 are the smallest among the eighteen tests. The mean case hardness varies from 634.0 to 730.2 HV, and the mean values of all tests exceed 600 HV, as shown in Table 5. The standard deviation varies from 10.97 to 34.61 HV and test L16 is the smallest among the eighteen tests. As shown in Table 6, the mean core hardness varies from 427.3 to 448.7 HV and the mean values are smaller than the value at the original settings. The standard deviation varies from 4.90 to 15.86 HV and test L5 is the smallest among the eighteen tests. The properties of case-treated timber screws are clearly altered under various case treatment conditions.

4.1 Case hardness

To obtain the optimum quality, ANOVA is performed to determine significant factors and optimum fabrication conditions. The contribution and confidence level of each factor shown in Table 7 could identify the significant factor affecting the case hardness of case-treated timber screws. The contribution of a factor is the percentage of the sum of squares (*SS*), that is, the percentage of the factor variance to the total quality loss.[14,15] The effect of a factor may be pooled to error if its confidence level or contribution is relatively small. It is obvious from the ANOVA table that the contribution of ammonia flow rate (A) is 52.7% of the total variation, which is the highest contributor to the variability of the experimental results. The contributions of carbon potential (F) and case treatment time (E) are 12.1 and 11.5%, which are the second and third highest contributions, respectively. However, the other four factors are not significant for the S/N ratio since their contributions are relatively small. By pooling the errors from the nonsignificant factors (B, C, D, and G), the error for the S/N ratio is estimated[15] and then the

Table 4
Experimental results for torsional strength.

Exp. No.*	T1	T2	T3	T4	T5	T6	T7	T8	T9	μ (N·m)	S	S/N ratio
L1	6.28	6.28	6.08	6.28	6.08	6.28	6.28	6.28	6.47	6.26	0.111	−4.91
L2	6.67	6.47	6.67	6.47	6.28	6.47	6.47	6.67	6.47	6.52	0.123	−6.12
L3	6.67	6.67	6.67	6.47	6.47	6.67	6.47	6.67	6.47	6.58	0.097	−6.39
L4	6.28	6.67	6.67	6.47	6.47	6.67	6.67	6.67	6.47	6.56	0.134	−6.30
L5	6.47	6.47	6.47	6.47	6.47	6.47	6.67	6.67	6.47	6.52	0.082	−6.11
L6	6.47	6.67	6.67	6.67	6.47	6.67	6.67	6.67	6.67	6.63	0.082	−6.56
L7	6.47	6.47	6.47	6.47	6.47	6.67	6.67	6.47	6.47	6.52	0.082	−6.11
L8	6.67	6.67	6.28	6.67	6.47	6.67	6.67	6.47	6.47	6.56	0.134	−6.30
L9	6.28	6.67	6.67	6.28	6.87	6.47	6.67	6.47	6.47	6.54	0.185	−6.23
L10	6.28	6.67	6.47	6.47	6.28	6.67	6.47	6.47	6.47	6.47	0.131	−5.93
L11	6.08	6.28	6.28	6.47	6.47	6.28	6.28	6.28	6.28	6.30	0.111	−5.12
L12	6.67	6.87	6.87	6.87	6.67	6.67	6.47	6.67	6.67	6.71	0.123	−6.92
L13	6.47	6.67	6.87	6.67	6.47	6.87	6.67	6.47	6.67	6.65	0.145	−6.66
L14	6.47	6.67	6.67	6.67	6.67	6.47	6.67	6.47	6.87	6.63	0.123	−6.57
L15	6.28	6.47	6.47	6.47	6.67	6.47	6.87	6.87	6.47	6.56	0.188	−6.32
L16	6.67	6.87	7.06	7.06	7.06	6.87	6.87	6.87	6.87	6.91	0.123	−7.65
L17	6.47	6.67	6.87	6.67	6.47	6.67	6.67	6.47	6.67	6.63	0.123	−6.57
L18	6.67	6.47	6.47	6.47	6.47	6.67	6.28	6.47	6.28	6.47	0.131	−5.93

*Experimental conditions as defined in Table 2.

Table 5
Experimental results for case hardness.

Exp. No.*	T1	T2	T3	T4	T5	T6	T7	T8	T9	μ (HV)	S	S/N ratio
L1	697	663	698	691	601	681	698	684	616	669.9	34.61	−37.8
L2	716	692	735	731	726	730	720	692	728	718.9	15.34	−41.6
L3	659	730	713	702	682	656	735	648	693	690.9	30.27	−39.6
L4	690	686	723	699	706	720	701	666	696	698.6	16.39	−40.0
L5	770	749	706	729	720	766	724	704	704	730.2	24.32	−42.4
L6	697	716	692	674	692	697	664	714	684	692.2	15.92	−39.4
L7	711	747	691	689	694	646	706	684	710	697.6	25.43	−40.1
L8	659	678	681	646	699	687	746	709	667	685.8	28.04	−39.1
L9	681	664	707	618	626	691	706	638	641	663.6	32.31	−37.1
L10	653	642	634	612	641	656	603	656	609	634.0	19.75	−31.9
L11	651	712	680	671	693	729	687	632	665	680.0	28.08	−38.6
L12	656	685	664	661	697	668	679	676	669	672.8	12.11	−37.4
L13	614	671	652	615	656	623	630	663	670	643.8	21.99	−33.8
L14	683	693	700	641	663	693	657	654	673	673.0	19.35	−37.6
L15	661	680	679	652	655	656	657	640	643	658.1	13.05	−35.5
L16	663	696	682	679	680	658	674	682	687	677.9	10.97	−37.9
L17	647	643	678	641	604	621	649	652	646	642.3	19.36	−33.4
L18	650	648	691	647	643	654	654	663	627	653.0	16.30	−34.9

*Experimental conditions as defined in Table 2.

Table 6
Experimental results for core hardness.

Exp. No.*	T1	T2	T3	T4	T5	T6	T7	T8	T9	μ (HV)	*S*
L1	431	446	436	434	449	466	461	421	423	440.8	15.86
L2	453	444	431	443	437	432	453	437	446	441.8	8.17
L3	441	420	427	424	443	435	433	433	436	432.4	7.58
L4	437	432	442	437	434	442	447	431	441	438.1	5.30
L5	433	437	443	446	432	436	437	444	440	438.7	4.90
L6	428	456	434	434	428	440	433	432	438	435.9	8.52
L7	450	456	461	454	446	447	431	439	454	448.7	9.22
L8	447	443	440	444	455	452	439	431	440	443.4	7.23
L9	462	434	441	454	432	438	454	444	459	446.4	11.09
L10	437	444	450	453	425	431	442	425	426	437.0	10.86
L11	436	451	421	437	452	433	437	439	450	439.6	10.05
L12	428	426	446	432	441	431	436	417	453	434.4	10.94
L13	440	419	418	425	413	445	438	412	436	427.3	12.57
L14	442	415	454	449	413	419	431	437	449	434.3	15.64
L15	450	438	454	448	434	451	461	454	437	447.4	9.14
L16	436	440	435	448	446	461	449	451	445	445.7	8.06
L17	452	451	441	444	452	429	411	433	448	440.1	13.70
L18	429	431	430	433	436	437	443	443	423	433.9	6.58

*Experimental conditions as defined in Table 2.

Table 7
ANOVA results of S/N ratio for case hardness.

Factor	*SS*	DOF	Var.	Contribution (%)
A	73.25	1	73.25	52.71
B	3.53	2	1.76	2.54
C	11.41	2	5.71	8.21
D	5.14	2	2.57	3.70
E	16.04	2	8.02	11.54
F	16.88	2	8.44	12.15
G	5.82	2	2.91	4.19
Others	6.90	4	1.72	4.96
Total	138.96	17	—	100.00

Pooling of errors

Factor	*SS*	DOF	Var.	*F*	Confidence (%)	Significance
A	73.25	1	73.25	26.80	99.98	Yes
B			Pooled			
C			Pooled			
D			Pooled			
E	16.04	2	8.02	2.93	90.83	Yes
F	16.88	2	8.44	3.09	91.72	Yes
G			Pooled			
Others			Pooled			
Error	32.80	12	2.73		S_{exp} = 1.65	
Total	138.96	17		*At least 90.00% confidence level		

SS, sum of squares; DOF, degree of freedom; Var., variance; *F*, *F*-ratio; S_{exp}, experimental error confidence levels are determined to be 100.0, 90.8, and 91.7% for ammonia flow rate (A), case treatment time (E), and carbon potential (F), respectively. That is, the three factors significantly affect the case hardness of case-treated timber screws with a confidence level of more than 90.0%.

Figure 4 illustrates the factor response diagram and the level averages of seven factors with respect to the S/N ratio. For each factor, the effect is the range of level averages and the maximum level average is the optimum level.(14,15) It is clearly revealed that, for the significant factors of ammonia flow rate (A), case treatment time (E), and carbon potential (F), Level 2 for ammonia flow rate (0.0 L/min, A2), Level 3 for case treatment time (60 min, E3) and Level 1 for carbon potential (0.9%, F1) are evidently optimum, as shown in Fig. 4. The effects of the other four factors are relatively small. The optimum levels are Level 3 for methanol flow rate (2.0 L/min, B3), Level 1 for feeding weight (600 kg/h, C1), Level 1 for case treatment temperature (860 °C, D1), and Level 2 for quenchant temperature (85 °C, G2).

4.2 Torsional strength

For the torsional strength of case-treated timber screws, the ANOVA results of S/N ratio are shown in Table 8. It is evident from Table 8 that the highest contributor to the variability of the experimental results is the case treatment time (E), whose contribution reaches 26.4%. The contributions of case treatment temperature (D) and methanol flow rate (B) are 21.1 and 19.2%, which are the second and third highest contributions, respectively. The other factors are not significant because their contributions are relatively small. By pooling the errors from the nonsignificant factors (A, C, F, and G), the error for the S/N ratio is estimated(15) and then the confidence levels are determined to be 91.8, 93.2, and 95.9% for methanol flow rate (B), case treatment temperature (D) and case treatment time (E), respectively. That is, the three factors significantly affect the torsional strength of case-treated timber screws, with a confidence level of more than 90.0%.

The factor response diagram and the level averages of seven factors with respect to the S/N ratio are illustrated in Fig. 5. It is clearly revealed that, for the significant factors of methanol flow rate (B), case treatment temperature (D), and case treatment time (E), Level 1 for methanol flow rate (1.0 L/min, B1), Level 1 for case treatment temperature (860 °C, D1), and Level 1 for

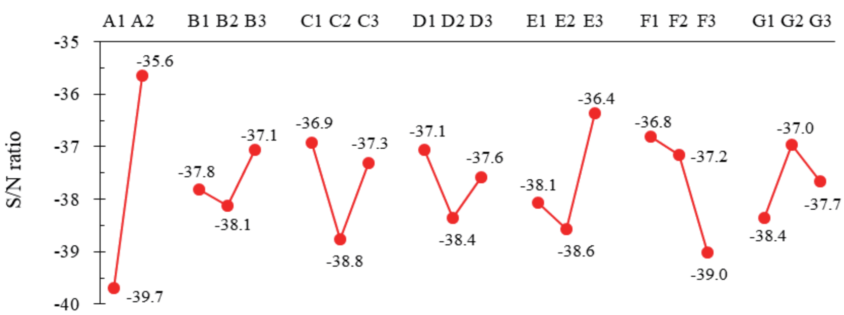

Fig. 4. (Color online) Factor response diagram for case hardness.

Table 8
ANOVA results of S/N ratio for torsional strength.

Factor	*SS*	DOF	Var.	Contribution (%)
A	0.39	1	0.39	6.3
B	1.20	2	0.60	19.2
C	0.20	2	0.10	3.2
D	1.32	2	0.66	21.1
E	1.65	2	0.82	26.4
F	0.07	2	0.03	1.0
G	0.24	2	0.12	3.8
Others	1.19	2	0.30	19.0
Total	6.25	17	—	100.0

Pooling of errors

Factor	*SS*	DOF	Var.	*F*	Confidence (%)	Significance
A			Pooled			
B	1.20	2	0.60	3.16	91.8	Yes
C			Pooled			
D	1.32	2	0.66	3.48	93.2	Yes
E	1.65	2	0.82	4.35	95.9	Yes
F			Pooled			
G			Pooled			
Others			Pooled			
Error	2.08	11	0.19		S_{exp} = 0.44	
Total	6.25	17		*At least 90.0% confidence level		

SS, sum of squares; DOF, degree of freedom; Var., variance; *F*, *F*-ratio; S_{exp}, experimental error

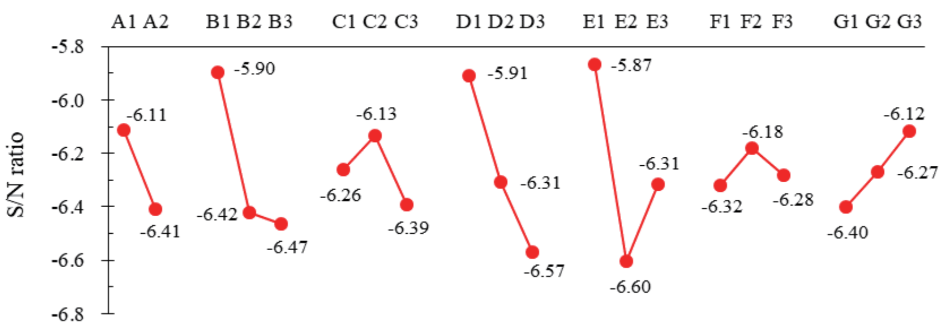

Fig. 5. (Color online) Factor response diagram for torsional strength.

case treatment time (40 min, E1) are evidently optimum, as shown in Fig. 5. The effects of the other four factors are relatively small. The optimum levels are Level 1 for ammonia flow rate (0.5 L/min, A1), Level 2 for feeding weight (700 kg/h, C2), Level 2 for carbon potential (1.0%, F2), and Level 3 for quenchant temperature (90 °C, G3).

With the results of the optimum analysis of the quality characteristics of case hardness and torsional strength, the optimum conditions are shown in Table 9. Case treatment primarily provides the needed hard, wear-resistant case for screws and torsional strength (drilling performance) may be increased as well. Ammonia flow rate (A) and carbon potential (F) are significant factors for case hardness. Therefore, the optimum levels are determined as Level 2

Table 9
Optimum condition table for case treatment.

	Factor	Case hardness	Torsional strength	Optimum
A:	Flow rate of ammonia (NH_3) (L/min)	A2*	A1	A2
B:	Flow rate of methanol (CH_3OH) (L/min)	B3	B1*	B1
C:	Feeding weight (kg/h)	C1	C2	C2
D:	Case treating temperature (°C)	D1	D1*	D1
E:	Case treating time (min)	E3*	E1*	E1
F:	Carbon potential (%)	F1*	F2	F1
G:	Temperature of quenchant (°C)	G2	G3	G2

*Significant factor

for ammonia flow rate (0.0 L/min, A2) and Level 1 for carbon potential (0.9%, F1). For torsional strength, methanol flow rate (B) and case treatment temperature (D) are significant. Hence, the optimum levels are determined as Level 1 for methanol flow rate (1.0 L/min, B1) and Level 1 for case treatment temperature (860 °C, D1). Case treatment time (E) is significant for both case hardness and torsional strength, and Level 1 (40 min, E1) is determined. The other two factors are not significant either for case hardness or torsional strength; thus, Level 2 for feeding weight (700 kg/h, C2) and Level 2 for quenchant temperature (85 °C, G2) are determined.

4.3 Confirmation experiments

To verify the predicted results, the timber screws are fabricated using the optimum levels A2, B1, C2, D1, E1, F1, and G2, as described in Table 9. Figures 6 and 7 show the nontreated, original (using Level 2's in Table 1), and optimal probability distributions for the case/core hardness and torsional strength of AISI 1022 timber screws, respectively.

It is observed that, through case treatment with the original settings, the mean case hardness is increased substantially by about 452 HV as compared with the nontreated results; the mean core hardness is also increased by about 288 HV and the deviations are increased, as shown in Fig. 6. Simultaneously, the mean torsional strength is markedly increased by about 3.7 N·m, as shown in Fig. 7, which is much greater than the target value of 4.5 N·m. Compared with the original results, as shown in Fig. 6, the optimum mean case hardness of 673.1 HV is higher than the original mean case hardness of 660.3 HV, and the deviation is slightly increased by about 0.8%. The optimum mean core hardness of 440.0 HV is decreased compared with the original mean core hardness of 460.6 HV, and the deviation is obviously decreased by about 38.9%. For torsional strength, as shown in Fig. 7, the optimum mean value of 5.30 N·m is considerably decreased compared with the original mean value of 6.56 N·m, and the deviation is obviously decreased by about 31.2%.

The new parameter settings evidently improve the performance measures over their values at the original settings. Therefore, the quality of case-treated AISI 1022 timber screws is effectively improved.

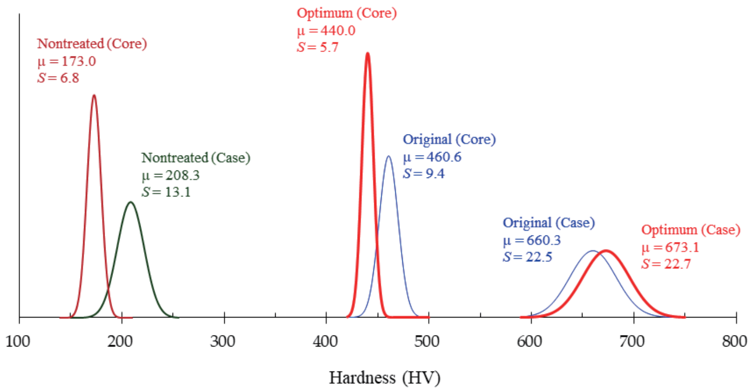

Fig. 6. (Color online) Probability distribution diagram for hardness.

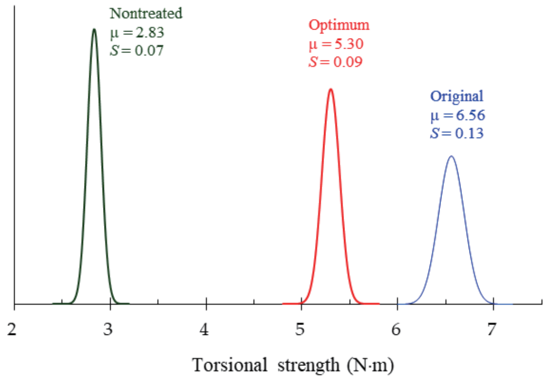

Fig. 7. (Color online) Probability distribution diagram for torsional strength.

5. Conclusions

The manufacturing processes of timber screws, which are widely used for construction work, include wire manufacturing, heading and threading, case treatment, and coating. A low-carbon steel wire of AISI 1022 is used to easily fabricate timber screws. The majority of case activity is performed to improve the strength without affecting the soft, tough interior of the screws in drilling operation. In this study, the Taguchi method is used to obtain optimum case treatment conditions to improve the mechanical properties of AISI 1022 timber screws. The quality of case-treated timber screws is affected by various factors, such as case treatment temperature, case treatment time, atmosphere composition, and tempering temperature. The effects of case treatment parameters affect the quality characteristics, such as case/core hardness and torsional strength.

Case treatment primarily provides a needed hard, wear-resistant case of screws and torsional strength (drilling performance) may be increased. It is experimentally revealed that ammonia flow rate (A), case treatment time (E), and carbon potential (F) are significant for case hardness, while methanol flow rate (B), case treatment temperature (D), and case treatment time (E) are significant for torsional strength; the determined levels are Level 2 for ammonia flow rate (0.0 L/min, A2), Level 1 for methanol flow rate (1.0 L/min, B1), Level 1 for case treatment temperature (860 ℃, D1), Level 1 for case treatment time (40 min, E1), and Level 1 for carbon potential (0.9%, F1). The other two factors are not significant either for case hardness or torsional strength; thus, Level 2 for feeding weight (700 kg/h, C2) and Level 2 for quenchant temperature (85 ℃, G2) are determined. In addition, the optimum mean case hardness is 673.1 HV, the optimum mean core hardness is 440.0 HV and, for torsional strength, the optimum mean value is 5.30 N·m. The new case treatment parameter settings evidently improve the performance measures over their values at the original settings. The strength of case-treated AISI 1022 timber screws is effectively improved. These results may be used as a reference for fastener manufacturers.

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References

1 C. A. Stickels: Heat Treating (ASM International, Materials Park, 2011).
2 J. I. Goldstein and A. E. Moren: Metall. Trans. A **9** (1978) 11.
3 T. V. Rajan, C. P. Sharma, and A. Sharma: Heat Treatment Principles and Techniques (Prentice-Hall of India Pvt. Ltd., New Delhi, 1994).
4 M. Li: Gear Technology **March/April** (2016).
5 F. O. Aramide, S. A. Ibitoye, I. O. Oladele, and J. O. Borode: Mater. Res. **12** (2009) 4.
6 Y. Peng, M. Zhang, J. Xiao, J. Dong, and C. Du: J. Mater. Res. **30** (2015) 6.
7 A. S. Ivanov, S. K. Greben'kov, and M. V. Bogdanova: Met. Sci. Heat Treat. **58** (2016) 1.
8 D. H. Herring: Fast. Tech. Int. **XXXIV** (2011) 3.
9 K.-M. Winter: J. Mater. Eng. Perform. **22** (2013) 7.
10 J. Slycke and T. Ericsson: J. Heat Treat. **2** (1981) 1.
11 L. M. Semenova, Y. S. Bakhracheva, and S. V. Semenov: Met. Sci. Heat Treat. **55** (2013) 1.
12 M. B. Karamiş and R. İpek: Appl. Surf. Sci. **119** (1997) 1.
13 M. L. Fares, A. Talhi, K. Chaoui, and M. Z. Touhami: Surf. Eng. **27** (2011) 8.
14 N. Logothetis: Managing for Total Quality: From Deming to Taguchi and SPC (Prentice Hall International, London, 1992).
15 H.-H. Lee: Taguchi Methods: Principles and Practices of Quality Design (Gau Lih Book, New Taipei City, 2008).
16 C.-C. Yang and X.-Y. Lin: J. Mech. Eng. Autom. **6** (2016) 3.

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