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Optimization of Carbonitrided AISI 1022 Self-drilling Tapping Screw Process Parameters Using Taguchi Approach

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Abstract **-** The manufacturing processes of self-drilling tapping screws, which are widely used for construction works, include wire-manufacturing, forming, heat treating, and coating. A low-carbon steel wire of AISI 1022 is used to easily fabricate into self-drilling tapping screws. The majority of carbonitriding activity is performed to improve the wear resistance without affecting the soft, tough interior of the screws in self-drilling operation. In this study, Taguchi method is used to obtain optimum carbonitriding conditions to improve the mechanical properties of AISI 1022 self-drilling tapping screws. The carbonitriding qualities of self-drilling tapping screws are affected by various factors, such as quenching temperature, carbonitriding time, atmosphere composition (carbon potential and ammonia level), tempering temperature and tempering time. The effects of carbonitriding parameters affect the quality characteristics, such as case hardness and core hardness. It is experimentally revealed that the factors of carbonitriding time and tempering temperature are significant for case hardness, while only tempering temperature is significant for core hardness. The optimum mean case hardness is 649.2HV, and the optimum mean core hardness is 439.7HV. The new carbonitriding parameter settings evidently improve the performance measures over their values at the original settings. The strength of the carbonitrided AISI 1022 self-drilling tapping screws is effectively improved. The results may be used as a reference for fastener manufacturers.

Keywords**:** Self-drilling tapping screw, Carbonitriding, Taguchi method, Case hardness

1. Introduction

The manufacturing processes of self-drilling tapping screws, as shown in Fig. 1, which are widely used for construction works, include wire-manufacturing, forming, heat treating, and coating. Low-carbon steel wires are usually used to fabricate into screws. In order to increase the strength of screws in self-drilling operation, case-hardening treatment is usually an essential process which is used to improve the wear resistance and not affect the soft, tough interior of the screws. This coalescence of hard surface and resistance to breakage is valuable in self-drilling tapping screws which have a very hard surface to resist wear, along with a tough interior to resist the breakage that occurs during self-drilling operation. Gas carburizing 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 carburizing. The process converts the outer layer of a screw into a high-carbon steel, with a content range of 0.9-1.2% carbon.

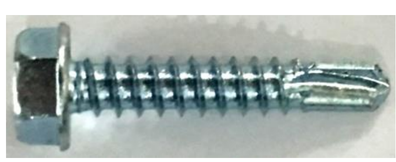

Fig. 1: Self-drilling tapping screws (#10×1” HW-BK).

Carbonitriding, a modified form of gas carburizing, by diffusing of both carbon and nitrogen into the surface layer enables the process to be carried out at lower temperatures and a shorter time than with carbon alone. Carbonitriding is used primarily to impart a hard, wear-resistant case. The case depth depends on the time and temperature of treatment. A carbonitriding case has better hardenability than a carburized case since nitrogen increases the hardenability of steel [2]. Carbonitriding is an excellent choice for low carbon fastener materials that require a uniform, but shallow case with good wear properties [3]. The combined diffusion profile of carbon and nitrogen applied in a carbonitriding process plays a major role, besides the process temperature. The reactions occurring during the carbonitriding process have been studied theoretically and experimentally [4]. Winter [5] presented a new system able to measure and control both the carbon potential and the nitrogen potential independently.

In this study, in order to obtain the optimum quality on carbonitriding treatment of AISI 1022 self-drilling tapping screws, a series of carbonitriding experiment is conducted in a continuous furnace. Various parameters affect the quality of carbonitriding such as quenching temperature, carbonitriding time, atmosphere composition (carbon potential and ammonia level), and tempering temperature. The effects of carbonitriding parameters affected the quality characteristics, such as case hardness and core hardness of self-drilling tapping screws are analyzed by using Taguchi method [6,7].

2. Experiment Design

Carburizing and carbonitriding are often used together to achieve much deeper case depths and better engineering performance for self-drilling tapping screws. A series of carbonitriding experiment on AISI 1022 self-drilling tapping screws is conducted in a continuous furnace, as shown in Fig. 2. In the furnace, zone 1 is for preheating; zones 2 and 3 are mainly for carburizing by adding propane (C_3H_8) at higher temperature of 870-880°C to give the desired total case depth; zones 4 and 5 are for carbonitriding by adding propane (C_3H_8) and ammonia (NH_3) in the lower temperature of 840-870°C to add the desired carbonitrided case depth; zone 6 is for quenching at lower operating temperature of 800-840°C; and then, the screws are oil quenched, followed by tempering in the temperature of 300-340°C.

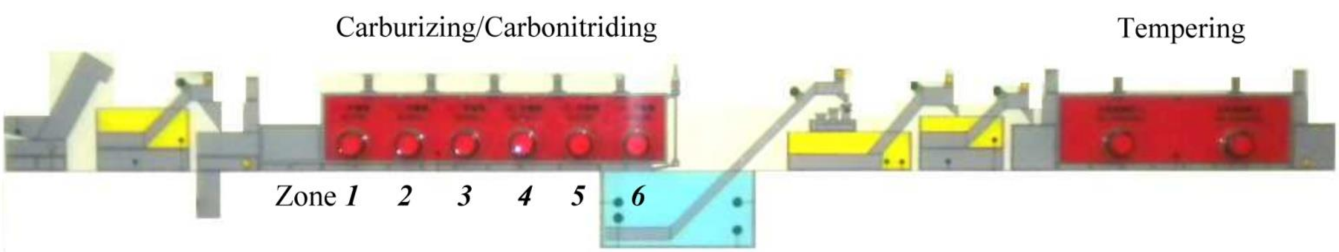

Fig. 2: The schematic illustration of a continuous furnace.

In order to evaluate the mechanical properties of the self-drilling tapping screws, eight controllable process factors are identified: 1 at two levels and 7 at three levels [6,7]. All factors and their levels are shown in Table 1. The parameters of Level 2 are the original carbonitriding process conditions, which was using in the company.

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

Factor	Level 1	Level 2	Level 3
A: Temperature of zone 3 (°C)	870	880	
B: Temperature of zone 5 (°C)	840	850	870
C: Temperature of zone 6 (°C)	800	820	840
D: Carbonitriding time (min)	40	50	60
E: Carbon potential (%)	1.0	0.9	0.8
F: Flow rate of ammonia (NH_3) (*l*/min)	0.6	0.5	0.4
G: Tempering temperature (°C)	300	320	340
H: Tempering time (min)	40	45	50

Taguchi method allows the changing of many factors at the same time in a systematic way, ensuring the reliable and independent study of the factors' effects. The orthogonal array table, $L_{18}(2^1 \times 3^7)$, is used as an experimental design for these eight factors [6,7], as listed in Table 2.

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

Exp. No.	A: Temperature of zone 3 (°C)	B: Temperature of zone 5 (°C)	C: Temperature of zone 6 (°C)	D: Carbonitriding time (min)	E: Carbon potential (%)	F: Flow rate of ammonia (*l*/min)	G: Tempering temperature (°C)	H: Tempering time (min)
L1	870	840	800	40	1.0	0.6	300	40
L2	870	840	820	50	0.9	0.5	320	45
L3	870	840	840	60	0.8	0.4	340	50
L4	870	850	800	40	0.9	0.5	340	50
L5	870	850	820	50	0.8	0.4	300	40
L6	870	850	840	60	1.0	0.6	320	45
L7	870	870	800	50	1.0	0.4	320	50
L8	870	870	820	60	0.9	0.6	340	40
L9	870	870	840	40	0.8	0.5	300	45
L10	880	840	800	60	0.8	0.5	320	40
L11	880	840	820	40	1.0	0.4	340	45
L12	880	840	840	50	0.9	0.6	300	50
L13	880	850	800	50	0.8	0.6	340	45
L14	880	850	820	60	1.0	0.5	300	50
L15	880	850	840	40	0.9	0.4	320	40
L16	880	870	800	60	0.9	0.4	300	45
L17	880	870	820	40	0.8	0.6	320	50
L18	880	870	840	50	1.0	0.5	340	40

In this study, two quality characteristics of the carbonitriding AISI 1022 self-drilling tapping screws, case hardness and core hardness as measured in Fig. 3, are investigated. Each test trial, including 9 specimens, is followed by each fabrication process and the results are then transformed to the S/N ratio (signal-to-noise ratio). For a non-treating screw, the case hardness of 229.0HV is measured on the tooth and the core hardness of 171.0HV is tested at the center of screw, as shown in Fig. 3. Since the hardness of workpiece may be increased by plastic flow [8], the case hardness is greater than the core hardness mainly due to the plastic work of threading.

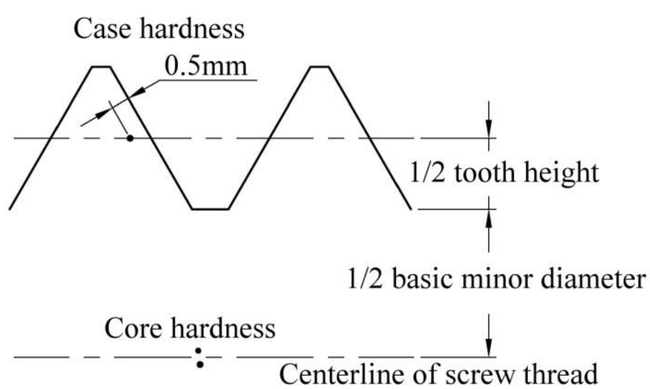

Fig. 3: The schematic illustration of measuring for case hardness and core hardness.

Carbonitriding primarily provides a needed hard, wear-resistant case of screws. Through carbonitriding, the strength of self-drilling tapping screws may be improved, and the case hardness, which is the main quality characteristic and is obtained from the Vickers hardness test, may be increased as well. Therefore, the case hardness of the self-drilling tapping screws should be exceeding 600HV, which is assigned by the company. Therefore, in terms of the desired characteristics for the case hardness, the greater the better, and the S/N ratio is [7].

$$SNR = -10 \log \frac{\sum_{i=1}^{n} 1/y_i^2}{n}, \quad (1)$$

where y_i is the case hardness and n is the test number of each trial.

Case hardening is used to improve the wear resistance of screws without affecting the soft, tough interior of the screws; and is useful in self-drilling tapping screws that have a very hard surface to resist wear, along with a tough interior to resist the breakage that occurs during operation. As assigned by the company, the core hardness of the self-drilling tapping screws should be between 300 and 500HV. Therefore, in terms of the desired characteristics for the core hardness, the smaller the better, and the S/N ratio is [7].

$$SNR = -10 \log \frac{\sum_{i=1}^{n} y_i^2}{n}, \quad (2)$$

where y_i is the core hardness and n is the test number of each trial.

Analysis of variance (ANOVA) is an effective method to determine the significant factors and the optimal fabrication conditions to obtain optimal quality. For Taguchi method, the experimental error is evaluated with ANOVA to carry out the significance test of the various factors. The nature of the interaction between factors is considered as experimental error [7]. If the effect of a factor in comparison to 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 influences the material property of the self-drilling tapping screws.

3. Results and Discussion

The experimental results of the core hardness and case hardness (mean, μ; standard deviation, *S*; and S/N ratio) of the carbonitrided self-drilling tapping screws are shown in Table 3.

Table 3: The experimental results for case hardness and core hardness.

Exp. No.	Case hardness			Core hardness		
	μ(HV)	*S*	S/N ratio	μ(HV)	*S*	S/N ratio
L1	616.8	10.60	55.80	430.0	14.86	-52.67
L2	629.3	8.77	55.98	420.2	7.24	-52.47
L3	613.3	8.80	55.75	410.8	7.73	-52.27
L4	610.3	4.90	55.71	413.8	8.01	-52.34
L5	629.0	5.94	55.97	432.9	5.64	-52.73
L6	620.6	8.28	55.85	420.4	6.15	-52.47
L7	620.0	4.39	55.85	417.0	9.91	-52.40
L8	616.0	7.04	55.79	415.0	6.00	-52.36
L9	620.7	8.17	55.86	428.3	8.66	-52.64
L10	613.3	4.80	55.75	430.4	5.81	-52.68
L11	611.9	4.86	55.73	411.8	9.48	-52.30
L12	631.9	6.17	56.01	428.3	6.56	-52.64
L13	618.2	8.96	55.82	419.3	8.00	-52.45
L14	631.0	11.10	56.00	435.6	5.96	-52.78
L15	615.9	8.10	55.79	423.3	4.90	-52.53
L16	629.4	6.02	55.98	428.1	10.75	-52.63
L17	613.8	7.14	55.76	422.9	4.81	-52.53
L18	611.6	4.72	55.73	426.9	5.93	-52.61
Ave.	619.6	7.15	55.84	423.1	7.58	-52.53

* Experimental conditions as defined in Table 2.

Compared with the measures of non-treating screws, the core hardness and case hardness are increased together, while the increment of case hardness (more than 380HV) is much more than core hardness (less than 270HV). The mean case hardness varies from 610.3 to 631.9HV, and the mean values of all tests are exceeding 600HV, as shown in Table 3. The standard deviation of test L7 is the smallest of the eighteen tests. As shown in Table 3, the mean core hardness varies from 410.8 to 435.6HV, and the standard deviation of test L17 is the smallest of the eighteen tests. The properties of carbonitrided self-drilling tapping screws are obviously altered with various carbonitriding process conditions.

3.1. Case Hardness

To obtain optimum quality, analysis of variance (ANOVA) is an effective method to determine significant factors and optimum fabrication conditions. The contribution and confidence level of each factor constructed in Table 4 could identify the significant factor affecting the case hardness of carbonitrided self-drilling tapping 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 [6,7]. 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 tempering temperature (G) is 54.73% of the total variation, which is the highest contributor to the variability of the experimental results. The contribution of carbonitriding time (D) is 24.39%, which is the second highest contribution. However, the other six factors are not significant for the S/N ratio because their contributions are relatively small. With the pooling of errors from the non-significant factors (A, B, C, E, F and H), the error estimation for the S/N ratio is obtained [7] and then the confidence levels are 99.3% and 100.0%, respectively, for carbonitriding time (D) and tempering temperature (G). That is, both factors, particularly the tempering temperature, significantly affect the case hardness of carbonitrided self-drilling tapping screws, with more than a 99.0% confidence level.

Table 4: Variance analysis table of signal-to-noise (S/N) ratio for case hardness.

Factor	*SS*	DOF	Var	Contribution
A	0.00001	1	0.00001	0.01%
B	0.00290	2	0.00145	1.62%
C	0.00907	2	0.00454	5.06%
D	0.04376	2	0.02188	24.39%
E	0.01152	2	0.00576	6.42%
F	0.00022	2	0.00011	0.12%
G	0.09819	2	0.04909	54.73%
H	0.01266	2	0.00633	7.06%
others	0.00106	2	0.00053	0.59%
Total	0.17940	17		100.00%

Pooling of errors

Factor	*SS*	DOF	Var	F	Confidence	Significance
A	Pooled					
B	Pooled					
C	Pooled					
D	0.04376	2	0.02188	7.59	99.3%	Yes
E	Pooled					
F	Pooled					
G	0.09819	2	0.04909	17.04	100.0%	Yes
H	Pooled					
others	Pooled					
Error	0.03745	13	0.00288	S_{exp} = 0.05		
Total	0.17940	17	*Note: At least 99.0% confidence			

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

Fig. 4 illustrates the factor response diagram and the level averages of eight factors with respect to the S/N ratio. For each factor, the effect is the range of the level averages and the maximum level average is the optimum level [6,7]. It is obviously revealed that, for the significant factors of carbonitriding time (D) and tempering temperature (G), Level 2 for carbonitriding time (50 min, D2) and Level 1 for tempering temperature (300 °C, G1) are evidently the optimum levels, as shown in Fig. 4. It is observed that their response is almost linear with the tempering temperature. That is, the case hardness increases with the decrease of the tempering temperature. The effects of the other six factors are relatively small. The optimum levels are Level 2 for the temperature of zone 3 (880°C, A2), Level 2 for temperature of zone 5 (850°C, B2), Level 2 for temperature of zone 6 (820°C, C2), Level 2 for carbon potential (0.9%, E2), Level 3 for flow rate of ammonia (0.4 l/min, F3), and Level 2 for tempering time (45 min, H2), respectively.

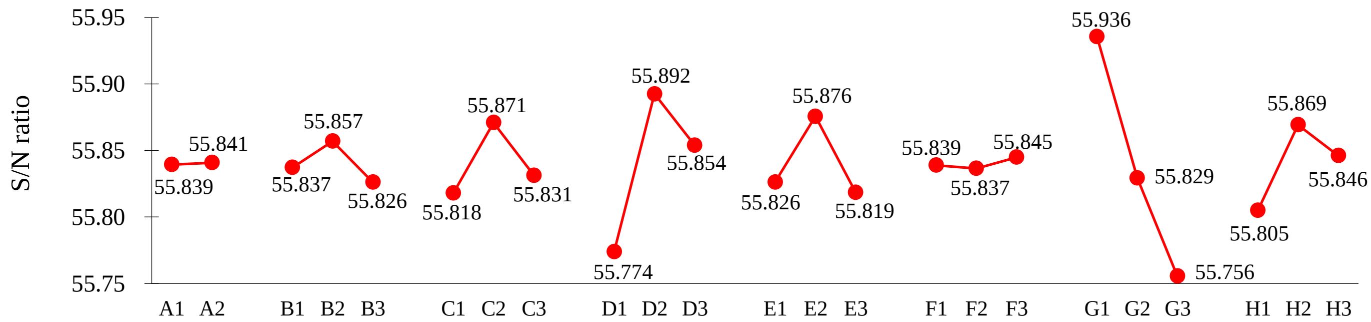

Fig. 4: The factor response diagram for case hardness.

3.2. Core Hardness

For the core hardness of the carbonitrided self-drilling tapping screws, the ANOVA table of S/N ratio is constructed in Table 5.

Table 5: Variance analysis table of signal-to-noise (S/N) ratio for core hardness.

Factor	*SS*	DOF	Var	Contribution
A	0.03404	1	0.03404	8.52%
B	0.00650	2	0.00325	1.63%
C	0.00004	2	0.00002	0.01%
D	0.00769	2	0.00385	1.92%
E	0.00983	2	0.00491	2.46%
F	0.03492	2	0.01746	8.74%
G	0.26093	2	0.13047	65.28%
H	0.04310	2	0.02155	10.78%
others	0.00265	2	0.00132	0.66%
Total	0.39969	17		100.00%

Pooling of errors

Factor	*SS*	DOF	Var	F	Confidence	Significance
A	Pooled					
B	Pooled					
C	Pooled					
D	Pooled					
E	Pooled					
F	Pooled					
G	0.26093	2	0.13047	14.10	100.0%	Yes
H	Pooled					
others	Pooled					
Error	0.13876	15	0.00925	S_{exp} = 0.10		
Total	0.39969	17	*Note: At least 99.0% confidence			

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

It is evident from Table 5 that the highest contributors to the variability of the experimental results is the tempering temperature (G), which contribution reaches up to 65.28% and is much higher than the other factors. The other factors are not significant because their contributions are relatively small. With the pooling of errors from the non-significant factors (A~F and H), the confidence level are 100% for the tempering temperature (G). That is, the core hardness of the carbonitrided self-drilling tapping screws is significantly affected by the tempering temperature with more than a 99.0% confidence level.

The factor response diagram and the level averages of eight factors with respect to the S/N ratio are illustrated in Fig. 5. Although the factor of Carbonitriding time (D) is significant for case hardness (Fig. 4) in this study, it is not significant for core hardness. As shown in Fig. 5, the effect of factor C, temperature of zone 6, is almost none which is as ANOVA analysis in Table 5. It is observed that the response is linear for the most significant factor, the tempering temperature (G). That is, the core hardness decreases with the increase of the tempering temperature. The optimum level is Level 3 for tempering temperature (340°C, G3). For the seven non-significant factors, the optimum levels are Level 1 for the temperature of zone 3 (870°C, A1), Level 1 for the temperature of zone 5 (840°C, B1) , Level 2 for temperature of zone 6 (820°C, C2), Level 1 for carbonitriding time (40 min, D1), Level 2 for carbon potential (0.9%, E2), Level 3 for flow rate of ammonia (0.4 l/min, F3) and Level 3 for the tempering time (50 min, H3), respectively, as shown in Fig. 5.

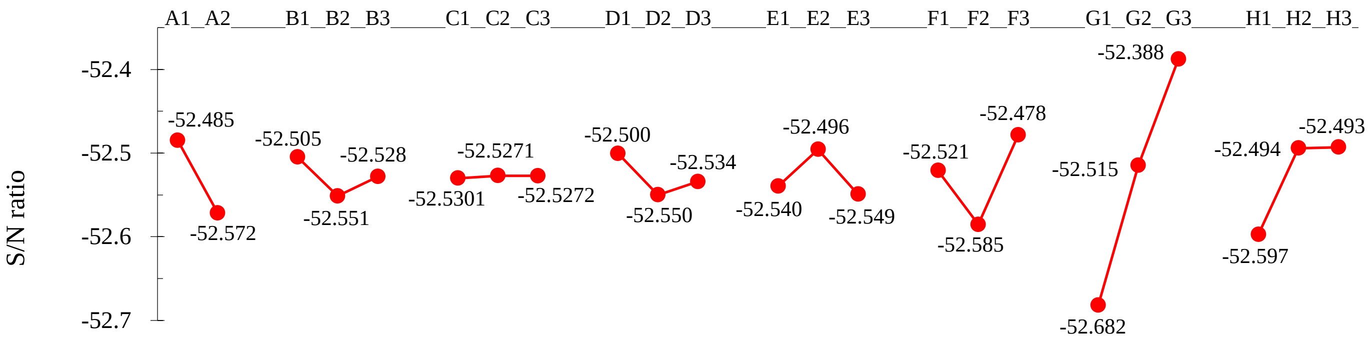

Fig. 5: The factor response diagram for core hardness.

With the optimum analysis for the quality characteristics of core hardness and case hardness, the optimum conditions are shown in Table 6. Carbonitriding primarily provides a needed hard, wear-resistant case of screws. Case hardness is then the main quality characteristic. The factors of carbonitriding time (D) and tempering temperature (G) are obviously significant for the case hardness. Therefore, the optimum levels are determined as Level 2 for the carbonitriding time (50 min, D2) and Level 1 for tempering temperature (300°C, G1). The other six factors are not significant either for case hardness or core hardness. Thus, Level 1 for the temperature of zone 3 (870°C, A1), Level 1 for the temperature of zone 5 (840°C, B1), Level 2 for the temperature of zone 6 (820°C, C2), Level 2 for carbon potential (0.9%, E2), Level 3 for flow rate of ammonia (0.4 l/min, F3) and Level 2 for the tempering time (45 min, H2) are determined.

Table 6: Optimum condition table for carbonitriding treatment.

Factor		Case hardness	Core hardness	Optimum
A:	Temperature of zone 3 (°C)	A2	A1	A1
B:	Temperature of zone 5 (°C)	B2	B1	B1
C:	Temperature of zone 6 (°C)	C2	C2	C2
D:	Carbonitriding time (min)	D2*	D1	D2
E:	Carbon potential (%)	E2	E2	E2
F:	Flow rate of ammonia (NH_3) (*l*/min)	F3	F3	F3
G:	Tempering temperature (°C)	G1*	G3*	G1
H:	Tempering time (min)	H2	H3	H2

* Significant factor.

3.3. Confirmatory Experiments

In order to verify the predicted results, the self-drilling tapping screws are fabricated using the optimum levels: A1, B1, C2, D2, E2, F3, G1 and H2, as described in Table 6. Fig. 6 shows the non-treated, original (using Level 2s in Table 1) and optimal probability distributions, respectively, for case hardness and core hardness of AISI 1022 self-drilling tapping screws. It is observed that, with carbonitriding treatment, the case hardness is increased substantially by about 390HV as compared to the non-treated results; the core hardness is also increased by about 252HV and the deviation is increased.

Compared with the original results, as shown in Fig. 6, the optimum mean case hardness of 649.2HV is not only higher than original mean case hardness of 619.6HV, but also the deviation is decreased by about 18%. The optimum mean core hardness of 439.7HV is slightly increased compared to the original mean core hardness of 423.1HV; and the deviation decreases by about 3% compared to the original result. The new parameter settings evidently improve the performance measures, such as case hardness, over their value at the original settings. Therefore, the quality of the carbonitrided AISI 1022 self-drilling tapping screws is effectively improved.

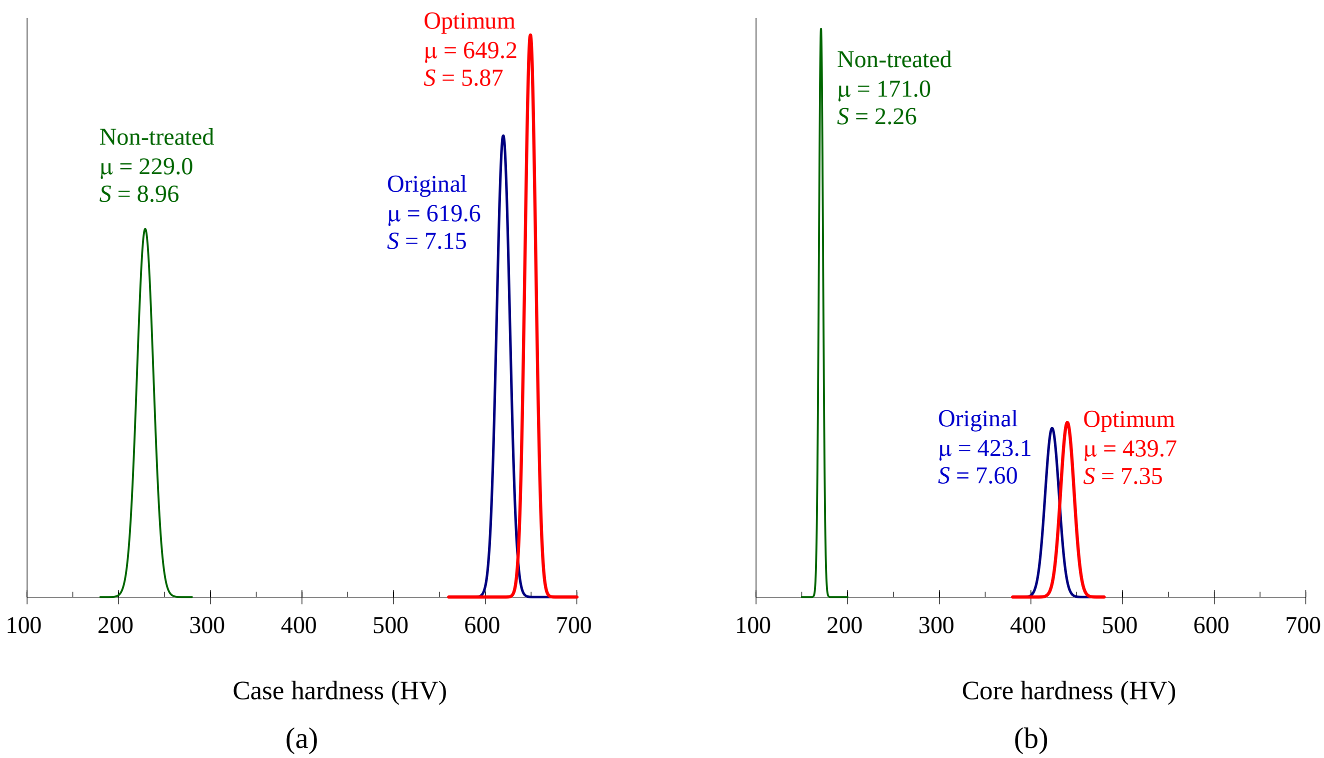

Fig. 6: The probability distribution diagram for (a) case hardness; (b) core hardness.

4. Conclusion

The manufacturing processes of self-drilling tapping screws, which are widely used for construction works, include wire-manufacturing, forming, heat treating, and coating. A low-carbon steel wire of AISI 1022 is used to easily fabricate into self-drilling tapping screws. The majority of carbonitriding activity is performed to improve the wear resistance without affecting the soft, tough interior of the screws in self-drilling operation. In this study, Taguchi method is used to obtain optimum carbonitriding conditions to improve the mechanical properties of AISI 1022 self-drilling tapping screws. The carbonitriding qualities of self-drilling tapping screws are affected by various factors, such as quenching temperature, carbonitriding time, atmosphere composition (carbon potential and ammonia level), tempering temperature and tempering time. The effects of carbonitriding parameters affect the quality characteristics, such as case hardness and core hardness.

Carbonitriding primarily provides a needed hard, wear-resistant case of screws. Case hardness is then the main quality characteristic. It is experimentally revealed that the factors of carbonitriding time (D) and tempering temperature (G) are significant for case hardness, while only tempering temperature (G) is significant for core hardness; the determined levels are Level 2 for the carbonitriding time (50 min, D2) and Level 1 for tempering temperature (300°C, G1). The other six factors are not significant either for case hardness or core hardness. Thus, Level 1 for the temperature of zone 3 (870°C, A1), Level 1 for the temperature of zone 5 (840°C, B1), Level 2 for the temperature of zone 6 (820°C, C2), Level 2 for carbon potential (0.9%, E2), Level 3 for flow rate of ammonia (0.4 l/min, F3) and Level 2 for the tempering time (45 min, H2) are determined. In addition, the optimum mean case hardness is 649.2HV, and the optimum mean core hardness is 439.7HV. The new carbonitriding parameter settings evidently improve the performance measures over their values at the original settings. The strength of the carbonitrided AISI 1022 self-drilling tapping screws is effectively improved. The results may be used as a reference for fastener manufacturers.

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