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# The Optimization of Carbonitriding Process for 1022 Self-drilling Tapping Screw with Taguchi Technique

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**Abstract:** *A low-carbon steel wire of AISI 1022 is used to easily fabricate into self-drilling tapping screws, which are widely used for construction works. 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 technique 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 quality characteristics of carbonitrided tapping screws, such as case hardness and core hardness, are investigated, and so are their process capabilities. It is experimentally revealed that the factors of carbonitriding time and tempering temperature are significant for case hardness. The optimum mean case hardness is 649.2HV. For the case hardness, the optimum process-capability ratio increases by about 200% compared to the original result. 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.*

***Keywords:****Self-drilling tapping screw, Carbonitriding, Taguchi technique, Case hardness, Process capability.*

## I. 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.

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

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. The carburizing temperature varies from 870 to 940°C and the gas atmosphere for carburizing is produced from liquid or gaseous hydrocarbons such as propane, butane or methane [2]. Effective case depth is an important factor and goal in gas carburizing, involving complicated procedures in the furnace and requiring precise control of many thermal parameters [3]. The effects of the carburizing temperature and time on the mechanical properties of mild steel carburized with activated carbon were studied [4] and was observed that the process of carburization, carburizing temperature and soaking time at carburizing temperature strongly influenced the mechanical properties of mild steels.

Carbonitriding is a modified form of gas carburizing, which 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 [5]. Carbonitriding is an excellent choice for low carbon fastener materials that require a uniform, but shallow case with good wear properties [6]. 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 [7]. Winter [8] presented a new system able to measure and control both the carbon potential and the nitrogen potential independently. Karamiş and İpek [9] investigated the wear behavior of carburized and carbonitrided AISI 1020 and 5115 steels. The carbonitrided 5115 steel has the highest wear resistance followed by carburized 5115, carbonitrided 1020 and carburized 1020 respectively. Fares et al. [10] investigated gaseous carbonitriding effects on improvement of surface characteristics of new hot working tool steel close to as either chromium AISI H11 or AISI H13. Microstructure and the diffusion mechanism suggested that high temperature gas carbonitriding process has the potential of improving the mechanical properties with shorter processing time.

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 [11,12].

## II. 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.

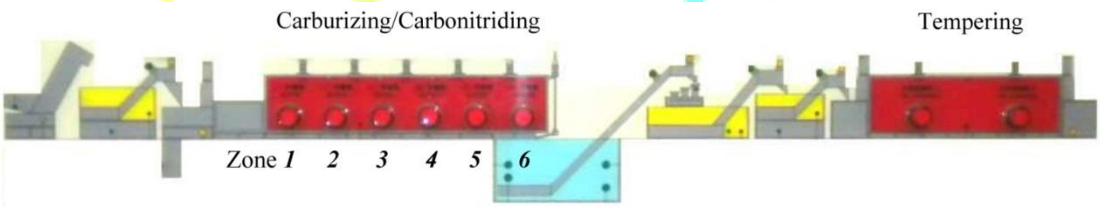



Fig. 2:The schematic illustration of a continuous furnace.

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. The carbonitriding procedure is shown in Fig. 3.

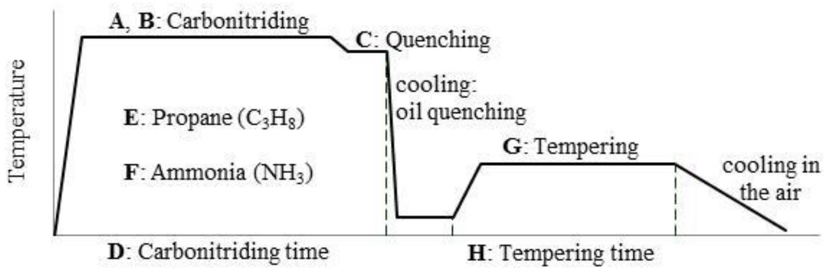



Fig. 3:The carbonitriding procedure.

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 [11,12]. All factors and their levels are shown in Table 1. The parameters of Level 2 are the original carbonitriding process conditions, which were 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, $L_{18}(2^1\times3^7)$, is used as an experimental design for these eight factors [11,12], as listed in Table 2.

Table 2: $L_{18}(2^1\times3^7)$ 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 |

Process capability is a measure of the nature behaviour of the process after special causes of variation are eliminated, and the basic purpose is to compare the "normal variation" of the process against the design tolerances to assess whether the process can meet those specifications [13].

In this study, two quality characteristics of the carbonitriding AISI 1022 self-drilling tapping screws, case hardness and core hardness as measured in Fig. 4, 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 measured at the center of screw, as shown in Fig. 4. Since the hardness of workpiece may be increased by plastic flow [14], the case hardness is greater than the core hardness mainly due to the plastic work of threading.

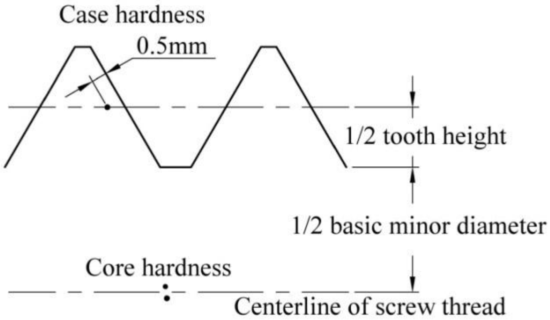



Fig. 4:The schematic illustration of measuring for case hardness and core hardness.

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. The case hardness of the self-drilling tapping screws should be exceeding 600HV, which is assigned by the company.For the case hardness of tapping screws, since only lower specification limit is necessary, the process-capability ratio[13]

$$\mathrm{CPL} = \frac{\mu - \mathrm{LSL}}{3S} \tag{1}$$

is measured, where μ is the process average of each trial. In terms of the desired characteristics for the case hardness, the larger the better, and the S/N ratio is therefore [12]

$$\mathrm{S/N} = -10\log\frac{\sum_{i=1}^{n} 1/y_i^2}{n}, \tag{2}$$

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.For the core hardness of tapping screws, the process capability is measured as [13]

$$C_p = \frac{\mathrm{USL} - \mathrm{LSL}}{6S}, \tag{3}$$

where USL is the upper specification limit, LSL is the lower specification limit and $S$ is the process standard deviation of each trial. In terms of the desired characteristics for the core hardness, the smaller the better, and the S/N ratio is [12]

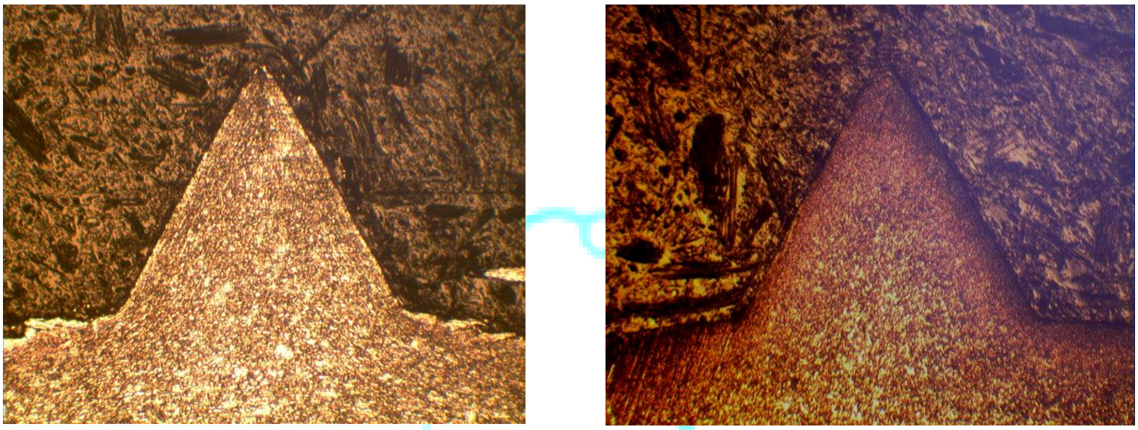
$$\mathrm{S/N} = -10\log\frac{\sum_{i=1}^{n} y_i^2}{n}, \tag{4}$$

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 [12]. 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 mechanical property of the self-drilling tapping screws.

## III. RESULTS AND DISCUSSION

The microstructure of self-drilling tapping screw is shown in Fig. 5a. This is not treated yet. Carbonitriding is the process of diffusing both carbon and nitrogen into the surface layer, as shown in Fig. 5b, to impart a hard, wear-resistant case.



(a) (b)

Fig. 5:Microstructures of tapping screw. (a) Non-treated; (b) Carbonitrided.

The experimental results of the core hardness and case hardness (mean, μ; standard deviation, *S*; S/N ratio; and process-capability ratio, CPL or $C_p$) of the carbonitrided self-drilling tapping screws are respectively shown in Tables 3 and 4.

Compared with the measures of non-treating screws, the case hardness and core 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, and the standard deviation of test *L7* is the smallest of the eighteen tests. However, the process-capability ratios ofmost of the eighteen tests (*L1*, *L3*, *L4*, *L6*, *L8*, *L9*, *L10*, *L11*, *L13*, *L14*, *L15*, *L17and L18*) are smaller than 1, which mean that their natural variations of the process are larger than the tolerance band given, then, their processes are not able to meet the specifications and incapable of ensuring 99.73%.of good self-drilling tapping screws [13].

Table 3: The experimental results of case hardness for tapping screws.

| Exp. No.* | T1 | T2 | T3 | T4 | T5 | T6 | T7 | T8 | T9 | μ(HV) | *S* | S/N Ratio | CPL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***L1*** | 607 | 600 | 614 | 621 | 613 | 628 | 613 | 620 | 635 | 616.8 | 10.60 | 55.80 | 0.53 |
| ***L2*** | 635 | 635 | 628 | 628 | 613 | 628 | 642 | 620 | 635 | 629.3 | 8.77 | 55.98 | 1.11 |
| ***L3*** | 621 | 620 | 614 | 606 | 600 | 605 | 628 | 613 | 613 | 613.3 | 8.80 | 55.75 | 0.50 |
| ***L4*** | 606 | 613 | 620 | 607 | 614 | 606 | 613 | 607 | 607 | 610.3 | 4.90 | 55.71 | 0.70 |
| ***L5*** | 635 | 620 | 635 | 635 | 628 | 632 | 628 | 620 | 628 | 629.0 | 5.94 | 55.97 | 1.63 |
| ***L6*** | 621 | 606 | 628 | 620 | 628 | 613 | 613 | 628 | 628 | 620.6 | 8.28 | 55.85 | 0.83 |
| ***L7*** | 614 | 621 | 621 | 621 | 628 | 621 | 620 | 621 | 613 | 620.0 | 4.39 | 55.85 | 1.52 |
| ***L8*** | 621 | 608 | 613 | 620 | 613 | 606 | 628 | 614 | 621 | 616.0 | 7.04 | 55.79 | 0.76 |
| ***L9*** | 628 | 614 | 613 | 621 | 621 | 635 | 613 | 628 | 613 | 620.7 | 8.17 | 55.86 | 0.84 |
| ***L10*** | 613 | 620 | 613 | 614 | 607 | 606 | 620 | 614 | 613 | 613.3 | 4.80 | 55.75 | 0.93 |
| ***L11*** | 614 | 621 | 613 | 606 | 614 | 606 | 613 | 607 | 613 | 611.9 | 4.86 | 55.73 | 0.82 |
| ***L12*** | 628 | 628 | 628 | 635 | 642 | 635 | 621 | 635 | 635 | 631.9 | 6.17 | 56.01 | 1.72 |
| ***L13*** | 606 | 628 | 606 | 613 | 628 | 628 | 621 | 620 | 614 | 618.2 | 8.96 | 55.82 | 0.68 |
| ***L14*** | 628 | 613 | 628 | 620 | 628 | 650 | 635 | 635 | 642 | 631.0 | 11.10 | 56.00 | 0.93 |
| ***L15*** | 628 | 606 | 614 | 614 | 614 | 620 | 606 | 613 | 628 | 615.9 | 8.10 | 55.79 | 0.65 |
| ***L16*** | 628 | 635 | 635 | 621 | 628 | 635 | 620 | 635 | 628 | 629.4 | 6.02 | 55.98 | 1.63 |
| ***L17*** | 607 | 614 | 606 | 628 | 613 | 621 | 607 | 614 | 614 | 613.8 | 7.14 | 55.76 | 0.64 |
| ***L18*** | 606 | 606 | 620 | 613 | 613 | 606 | 614 | 613 | 613 | 611.6 | 4.72 | 55.73 | 0.82 |
| **Ave.** | | | | | | | | | | 619.6 | 7.15 | 55.84 | 0.96 |

*: Experimental conditions as defined in Table 2.

Table 4: The experimental results of core hardness for tapping screws.

| Exp. No.* | T1 | T2 | T3 | T4 | T5 | T6 | T7 | T8 | T9 | μ(HV) | *S* | S/N Ratio | $C_P$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***L1*** | 438 | 438 | 426 | 430 | 440 | 443 | 438 | 395 | 422 | 430.0 | 14.86 | -52.67 | 2.24 |
| ***L2*** | 426 | 422 | 418 | 426 | 430 | 406 | 418 | 422 | 414 | 420.2 | 7.24 | -52.47 | 4.60 |
| ***L3*** | 422 | 403 | 403 | 414 | 414 | 410 | 422 | 406 | 403 | 410.8 | 7.73 | -52.27 | 4.31 |
| ***L4*** | 418 | 403 | 418 | 418 | 418 | 414 | 426 | 403 | 406 | 413.8 | 8.01 | -52.34 | 4.16 |
| ***L5*** | 434 | 426 | 430 | 443 | 430 | 434 | 439 | 426 | 434 | 432.9 | 5.64 | -52.73 | 5.91 |
| ***L6*** | 414 | 410 | 418 | 422 | 422 | 426 | 430 | 418 | 424 | 420.4 | 6.15 | -52.47 | 5.42 |
| ***L7*** | 403 | 403 | 422 | 422 | 418 | 426 | 426 | 407 | 426 | 417.0 | 9.91 | -52.40 | 3.36 |
| ***L8*** | 414 | 403 | 422 | 414 | 418 | 422 | 418 | 410 | 414 | 415.0 | 6.00 | -52.36 | 5.56 |
| ***L9*** | 430 | 426 | 426 | 426 | 434 | 439 | 438 | 426 | 410 | 428.3 | 8.66 | -52.64 | 3.85 |
| ***L10*** | 434 | 426 | 430 | 438 | 422 | 422 | 434 | 434 | 434 | 430.4 | 5.81 | -52.68 | 5.74 |
| ***L11*** | 418 | 403 | 418 | 422 | 399 | 418 | 422 | 403 | 403 | 411.8 | 9.48 | -52.30 | 3.51 |
| ***L12*** | 434 | 418 | 426 | 422 | 426 | 434 | 430 | 426 | 439 | 428.3 | 6.56 | -52.64 | 5.08 |
| ***L13*** | 426 | 406 | 414 | 430 | 426 | 422 | 422 | 410 | 418 | 419.3 | 8.00 | -52.45 | 4.17 |
| ***L14*** | 430 | 430 | 438 | 430 | 430 | 447 | 439 | 438 | 438 | 435.6 | 5.96 | -52.78 | 5.59 |
| ***L15*** | 426 | 414 | 426 | 426 | 422 | 422 | 430 | 418 | 426 | 423.3 | 4.90 | -52.53 | 6.80 |
| ***L16*** | 422 | 406 | 434 | 420 | 434 | 430 | 443 | 430 | 434 | 428.1 | 10.75 | -52.63 | 3.10 |
| ***L17*** | 422 | 422 | 422 | 418 | 426 | 426 | 426 | 414 | 430 | 422.9 | 4.81 | -52.53 | 6.93 |
| ***L18*** | 430 | 430 | 418 | 422 | 434 | 422 | 422 | 434 | 430 | 426.9 | 5.93 | -52.61 | 5.63 |
| **Ave.** | | | | | | | | | | 423.1 | 7.58 | -52.53 | 4.78 |

*: Experimental conditions as defined in Table 2.

As shown in Table 4, the means of core hardness vary from 410.8 to 435.6HV, which are all within the specified range of 300-500 HV, and the standard deviations of test *L17* and *L1*are respectively the smallest and the greatest. The process-capability ratios of all eighteen tests are larger than 1, which mean that the natural variations of the process are smaller than the tolerance band given.

The properties of carbonitrided self-drilling tapping screws are obviously varied with various carbonitriding process conditions.

### *III.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 5 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 [11,12]. 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 [12] 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.

Fig. 6 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 [11,12]. As shown in Fig. 6, the original levels (Level 2) are not all the optimum fabricating parameters for case hardness. It is revealed that, for the significant factors of carbonitriding time (D) and tempering temperature (G), Level 2 for carbonitriding time (50min, D2) and Level 1 for tempering temperature (300°C, G1) are evidently the optimum levels, as shown in Fig. 6. It is observed that its 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.

Table 5: 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.

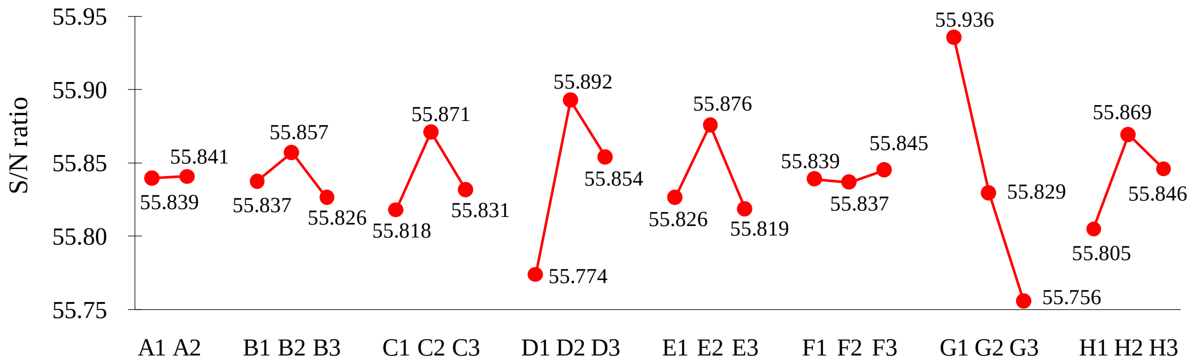



Fig. 6:The factor response diagram for case hardness.

### *III.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 6. It is evident from Table 6 that the highest contributor 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 dominant inference on core hardness of the carbonitrided self-drilling tapping screws is the tempering temperature with more than a 99.9% confidence level.

The factor response diagram and the level averages of eight factors with respect to the S/N ratio are illustrated in Fig. 7. Although the factor of carbonitriding time (D) is significant for case hardness (Fig. 6) in this study, it is not significant for core hardness. As shown in Fig. 7, the effect of factor C, temperature of zone 6, is almost none which is as ANOVA analysis in Table 6. 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. 7.

Table 6: 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 99.9% confidence | | |

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

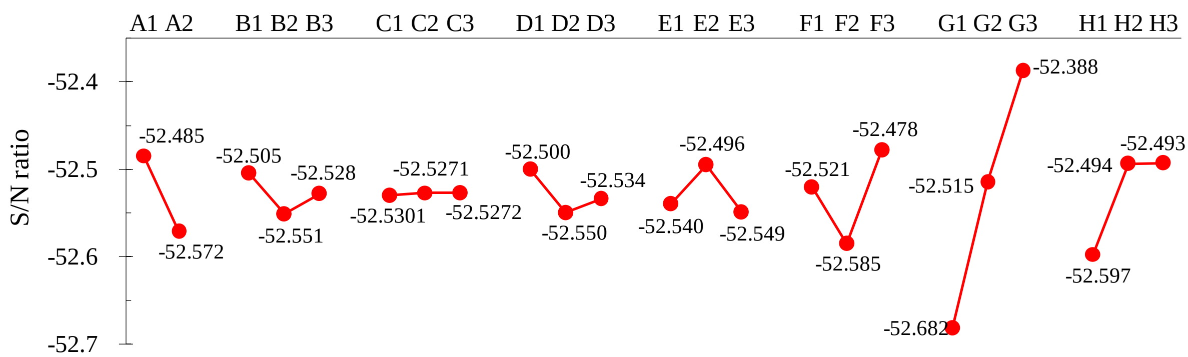



Fig. 7:The factor response diagram for core hardness.

With the optimum analysis for the quality characteristics of core hardness and case hardness, the optimum conditions are shown in Table 7. 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 7: 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.

### *III.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 7. Variation is the inability to perform a task consistently according to a specification [13]. Observe Fig. 8, where the natural variations of the process [13] of the eighteen tests together with the confirmatory experiment (optimum) and the operation with the original settings (using Level 2s in Table 1), including the given specification limit/spans, are plotted in the figure for the case hardness and core hardness of AISI 1022 self-drilling tapping screws.

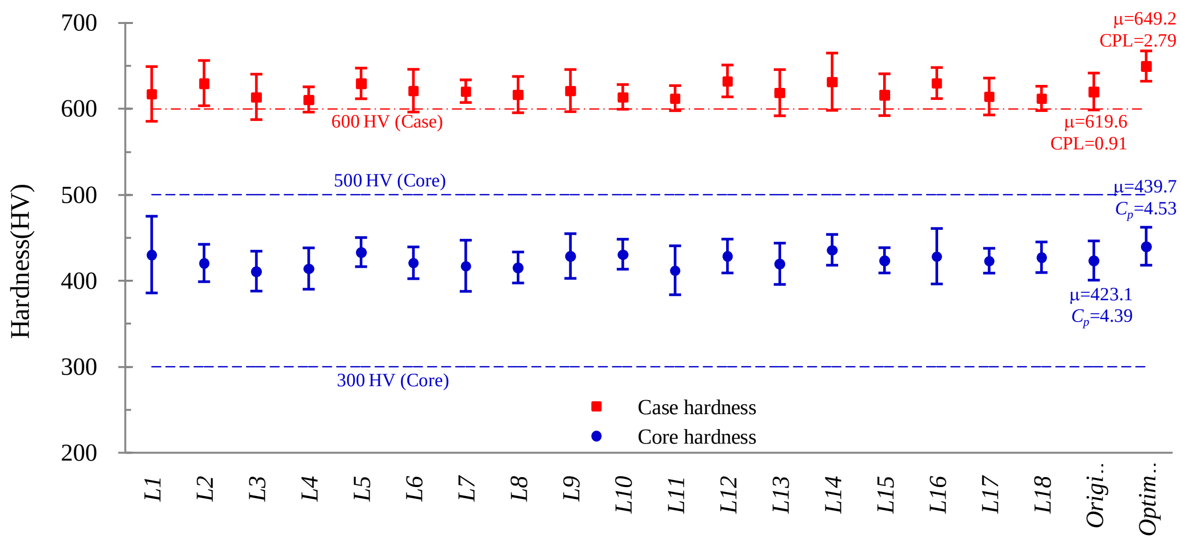



Fig. 8:The natural variation of the process for the case and core hardness.

Compared with the results of the eighteen tests, the optimum mean core hardness of 439.7HV is increased in comparison with the average (423.1HV in Table 4) and the process natural variation is smaller than the given tolerance band, as shown in Fig. 8. The optimum process-capability ratio, $C_p$= 4.53, which is slightly larger than the value, $C_p$= 4.39, at the original settings, is much larger than 1. Although the core hardness of carbonitrided screws meets the requirement of specification for the eighteen tests, for the case hardness as shown in Fig. 8, the process natural variations of the most of tests (except tests*L2*, *L5*, *L7*, *L12* and *L16*) are less than the lower specification limit, and so is the measure at the original settings. Their process-capability ratios are smaller than 1. This means that the process is incapable of ensuring 99.73% of good carbonitrided screws [13].

The optimum mean case hardness of 649.2HV is larger than not only the eighteen tests (Table 3),but alsothe measure at the original settings (Fig. 8).The optimum process-capability ratio reaches up to CPL = 2.79, as shown in Fig. 8, which increases by about 200% compared to the original result. This means that the process is more capable of ensuring 99.73% of good products in case hardness. Therefore, the new parameter settings evidently improve the performance measures, such as case hardness, over their value at the original settings. The quality of the carbonitrided AISI 1022 self-drilling tapping screws is effectively improved.

## IV. CONCLUSIONS

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. In this study, Taguchi method is used to obtain optimum carbonitriding conditions to improve the mechanical properties of AISI 1022 self-drilling tapping screws.

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 (50min, 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 core hardness meets the requirement of specification for the eighteen tests; for the case hardness, the optimum process-capability ratio reaches up to CPL = 2.79, which increases by about 200% compared to the original result. Therefore, the optimum process is more capable of ensuring 99.73% of good self-drilling tapping screws. 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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