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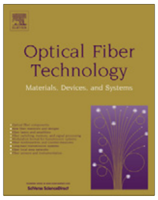

# Enhancement of process capability for strip force of tight sets of optical fiber using Taguchi's Quality Engineering

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## ABSTRACT

Strip force is the key to identifying the quality of product during manufacturing tight sets of fiber. This study used Integrated computer-aided manufacturing DEFinition 0 (IDEF0) modeling to discuss detailed cladding processes of tight sets of fiber in transnational optical connector manufacturing. The results showed that, the key factor causing an instable interface connection is the extruder adjustment process. The factors causing improper strip force were analyzed through literature, practice, and gray relational analysis. The parameters design method of Taguchi's Quality Engineering was used to determine the optimal experimental combinations for processes of tight sets of fiber. This study employed case empirical analysis to obtain a model for improving the process of strip force of tight sets of fiber, and determines the correlation factors that affect the processes of quality for tight sets of fiber. The findings indicated that, process capability index ($C_{PK}$) increased significantly, which can facilitate improvement of the product process capability and quality. The empirical results can serve as a reference for improving the product quality of the optical fiber industry.

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## 1. Introduction

With the development of Fiber to the Home (FTTH), the demand for optical fiber networks is increased; hence, optical fiber connection technology has become more important. The development of new products is the focus of attention and investment for enterprises [1]. Robust design suggested by Su [2] is a method of improving quality through engineering optimization. Taguchi's Quality Engineering (referred to as Taguchi methods), as created by Taguchi, is an experimental method based on robust design. By using this method, an orthogonal array is selected according to factors affecting quality, and then measured values of quality characteristics obtained from the experiment are converted into Signal-to-Noise ratio (SN) (see Appendix A). Upon further analysis, the parameters level in this group is used for production. The average value of quality characteristics will approach to target value, with the smallest variation. Lin [3] suggested that fiber optic connectors are bridges linking the key elements of optical communication devices. Among them, the ferrules used to position and align fibers are essential and the most critical component for fiber optic connectors. In order to reduce the eccentricity values for the required insertion loss, the Taguchi method is first used to simplify the optimization problems of the injection molding process.

This study used Integrated computer-aided manufacturing DEFinition 0 (IDEF0) (see Appendix B), gray relational analysis and Taguchi's Quality Engineering in order to evaluate and discuss product Research and Development (R&D) processes of transnational optical connector manufacturers, and intended to determine a suitable R&D model for tight sets of fiber. The analysis result can be used as reference for creating environments for tight sets of fiber quality and development in the optical communication industry. Thus, the study aimed to (1) improve product process capability and existing product quality; and (2) construct standard operational procedures defined by process parameters of tight sets of fiber [2–5].

## 2. Research process and case analysis

This study used IDEF0 to define the management system of new products [4,6], then measured and tested the strip force of tight sets of fiber, and analyzed current situations of process. It then used gray relational analysis and Taguchi's Quality Engineering to improve key points and parameters. Finally, it conducted process standardization and control plans for optimal process parameters [1,3]. The research process was as follows.

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### 2.1. Define

This study found tight sets of fiber in the production line meet the range required by international standard GR-409 (Newton: N) for explored process quality improvement of tight sets of fiber of transnational optical connector manufacturers. However, polyvinyl chloride (PVC) strip force of optical fiber outer cladding is larger than normal and may cause a breakdown of fiber used for optical connectors. Regarding the focus of post-process customer demands, this study aimed to improve the strip force of optical fiber, and then, identified core issues and described project description in view of the process flow. The tight sets of fiber are as shown in Fig. 1.

The development management system of a transnational optical connector manufacturer was coded according to IDEF0 coding principle, and their corresponding positions in IDEF0 model can be found. Operations of systems and hierarchical structures were presented using IDEF0, and A-0 page of the model represented Layer 0 and the name of the model. After expansion, the first layer was presented, which showed operations A1–A6. Each operation can be expanded to the second and third layers. After information and objects of the functions are defined, users can understand system functions and operations through graphics and hierarchy for further communication and discussion and select proper hierarchy for parameters design analysis of the Taguchi method.

The tight sets of fiber in production meet 1.3–13.3 N, as specified by international standard GR-409; however, many finished products are in upper limit of the specifications, and a too great strip force of tight sets of fiber may cause breakdowns of optical fiber, while too small a strip force may cause a clearance between the PVC cladding and optical fiber. During baking, gel may infiltrate into the clearance, resulting in product defect. In this study, IDEF0 modeling was employed to discuss the detailed cladding process of tight sets of fiber from top to bottom. It was found that a key factor causing instable interface connection was the extruder adjustment process. After measurement and analysis, parameters design of Taguchi was used to determine the optimal experimental combination for process improvement.

### 2.2. Measure

Measurement purposes were to obtain correct data for planning and the following corrective measures. Based on the observable data, the characteristics of interface binding force of PVC cladding stage were quantified, and a strip force of $\Phi$0.9 mm tight sets of fiber was defined as follows: PVC is used as the material to be improved, strip 15 mm ± 1.5 mm tight buffer coating to 125 μm glass coating; the strip force in the international standard GR409 is 1.3–13.3 N. To prove the reliability of the measurement system developed by the case company, a testing machine developed by the case company was used for testing, and process capability analysis was conducted for tested data. From the above experiment, measurement tolerance of equipment was ±1 N, and process capability index ($C_{PK}$) (see Appendix C) is generally regarded as evaluation indicator. $C_{PK} < 1$ denotes a defect, $1 \leqq C_{PK} < 1.33$ denotes warning, and $C_{PK} \geqq 1.33$ denotes acceptance. Based upon the analysis results of process capability using the measurement system, process capability index $C_{PK} = 1.68 > 1.33$, which showed the variation of the measurement system was smaller. This measurement system can meet experimental requirements.

### 2.3. Analyze

After the system measurement was proved reliable, samples were taken from stock to measure their average strip force and analyze current process capabilities of tight sets of fiber. The process capability analysis assumed quality capability when the known quality factors of process were controlled under normal conditions. Based on current situations, this obtained process capability indictor $C_{PK} = 0.92 < 1.33$, which showed quality was instable and process capability was inadequate, thus, further improvement was required. The analysis results of process capability are shown in Fig. 2.

From the above experiment, room for improvement was greater due to instable quality and inadequate process capability. The experimental process of tight sets of fiber adopted Taguchi's Quality Engineering to determine the optimal factor level combination to solve instable quality and inadequate process capability. Regarding quality features, the interface binding force of tight sets of fiber was static function, and strip force was expected to be close to 7.3 N ± 1 N. SN calculation of quality characteristics belongs to the nominal-the-best (NTB) characteristics (see Appendix A). First, machine adjustment processes, which affect interface binding force, were presented in a flow chart in order to analyze instable factors affecting strip force, and then, determine the key steps affecting process in the flow chart and solve the problems. The adjustment process is shown in Fig. 3.

In order to determine the key flow affecting process and solve the problems, this study, and relevant operators, considered correlation costs and influences of 10 different experimental factors, and selected four experimental factors according to priority, and then, reviewed and analyzed operating process flows of tight sets of fiber through experience, brainstorming, and gray relational analysis. The factors that may cause defective interface binding can be separated into controlled factors (experiment factors) and fixed factors. Upon discussion with relevant engineers, the four factors, machine head pressure (bar), extrusion temperature °C of machine head, cooling water temperature °C, and preheat temperature °C of optical fiber are independent. The interaction between the factors is small, and experimental cost is lower. The interaction effect can be regarded as a part of experimental error, then, the key factors affecting quality can be discussed by using Taguchi's Quality Engineering.

The degree of the relationships among sub-systems or elements could be evaluated through gray relational analysis [5,7], and important influential factors regarding development trends are then determined in order to learn the major features of the system through the following steps.

Step 1: Normalize original data. Normalize by dividing the original data $x_i(k)$ with the mean value of the sequence shown in:

$$r_i(k) = \frac{x_i(k)}{\sum_{k=1}^{N} \frac{x_i(k)}{N}}, \quad i = a, \ldots, d \quad k = A, \ldots, N \tag{1}$$

Step 2: Designate the standard sequence and calculate the difference sequence. Take the mean value as the standard sequence, i.e. sequence 0; the difference sequence $\Delta_{0i}(k)$ indicates the absolute difference of elements $k$ between the other sequence $i$ and the standard sequence 0, as expressed in:

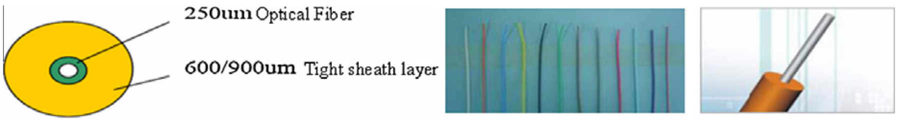

**Fig. 1.** 12-Color 0.9 mm tight sets of fiber.

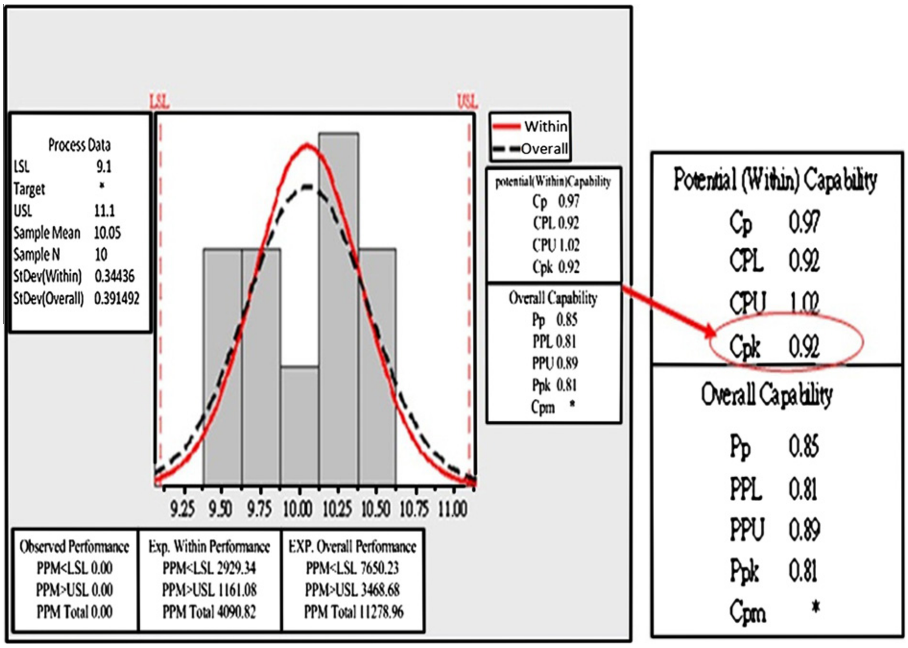

**Fig. 2.** Process capability analysis of tight sets of fiber.

$$\varDelta_{0i}(k) = |r_0(k) - r_i(k)|, \quad i = 1, 2, 3, \ldots \quad k = A, \ldots, N \tag{2}$$

Step 3: Calculate maximal difference $\varDelta_{\max}$ and minimal difference $\varDelta_{\min}$ as expressed in:

$$\varDelta_{\max} = \underset{i,k}{\mathrm{Max}}\, \varDelta_{0i}(k) \tag{3}$$

$$\varDelta_{\min} = \underset{i,k}{\mathrm{Min}}\, \varDelta_{0i}(k) \tag{4}$$

Step 4: Calculate gray relational coefficient: $\gamma_{0i}(k)$.

The relational coefficient: $\gamma_{0i}(k)$ is defined below, of which $\varsigma$ is the adjustment factor, as shown in Eq. (5).

$$\gamma_{0i}(k) = \frac{\varDelta_{\min} + \varsigma \cdot \varDelta_{\max}}{\varDelta_{0i}(k) + \varsigma \cdot \varDelta_{\max}} \tag{5}$$

Step 5: Calculate the gray relationship $\varGamma_{0i}$ between each sequence and the standard sequence. The gray relationship $\varGamma_{0i}$ is defined as in:

$$\varGamma_{0i} = \sum_{k=A}^{N} \frac{\gamma_{0i}(k)}{N} \tag{6}$$

Step 6: Conduct sequencing according to the gray relationship.

### 2.4. Improve

After consultation with three process engineers, the four experiment factors, namely, machine head pressure, extrusion temperature of machine head, cooling water, and preheat temperature had three levels, thus, an orthogonal array of $L_9(3^4)$ was selected for experiment. The selection criteria of factors levels is ±10% (deviation) of current level (191 bar, 173 °C, 40 °C and 190 °C), and three levels are selected as experimental basis. See Table 1 for levels of each factor.

The main effects of SN and mean can be determined from the above experiment, as shown in Figs. 4 and 5. The purpose of the experiment was nominal-the-best characteristics, which required a fixed target value. In addition to SN, which is used for minimizing variation, adjustment factors can be used to adjust the mean to the target value. This study utilized a two-stage optimization procedure, as suggested by Taguichi [2]:

Step 1: maximize SN to reduce susceptibility to noise. In this step, mean is temporarily ignored, and the combination of factor levels A2, B3, C1, and D2 can be selected.

Step 2: adjust mean to target value. In this step, a suitable adjustment factor was selected to adjust the mean to the target value; adjust factor C to level 2, factor D to level 3. After adjustments, based on the two-step optimization procedure, the combination of A2 B3 C2 D3 is selected.

Next, analysis of variance (ANOVA) was conducted, *F* value of factor *A* was 16.71, and *F* value of factor *B* was 6.8, both *F* values were greater than 4; the contribution rates of factors *A* and *B* were 61.58% and 22.73%, respectively, and the percentage of the error term was 15.69%. Accordingly, *A* and *B* factors had significant impact, and the impact of factor *A* was the most significant. The relevant data are shown in Table 2.

The last step of parameter design is validation testing, and this is a key step, which main purpose is to verify whether the conclusions are correct through data analysis; first, the estimated confidence interval of average value under 95% of optimal conditions is 35.28 ± 3.0 = [32.28, 38.28]. The validation test is used to verify whether the average value under optimal conditions is effective, thus, validation testing is conducted five times, according to the combinations of levels of optimal controlled factors. In each test, four observed values are taken, totaling to 20 observed values. Through equation, 95% of confidence interval of anticipated SN is calculated as 35.28 ± 3.5 = [31.78, 38.78]. From the above validation test, the average SN is 34.6276, and the confidence interval of anticipated SN in validation test is [31.78 and 38.78], and the mean falls into this confidence interval, meaning validation testing is successful.

After successful validation testing, the response value of validation test for Table 1 was used for process capability analysis; the average strip force was calculated as 7.651 N using the response value from the validation test, and the process capability $C_{PK} = 1.41$, which was greater than $C_{PK} = 0.92$, is superior to the eligibility criteria $C_{PK} = 1.33$. In this study, the combination of A2 B3 C2 D3 denotes the optimal process parameters for manufacturing tight sets of fiber, and can actually increase process capability and quality stability. The improved process capability is shown in Fig. 6.

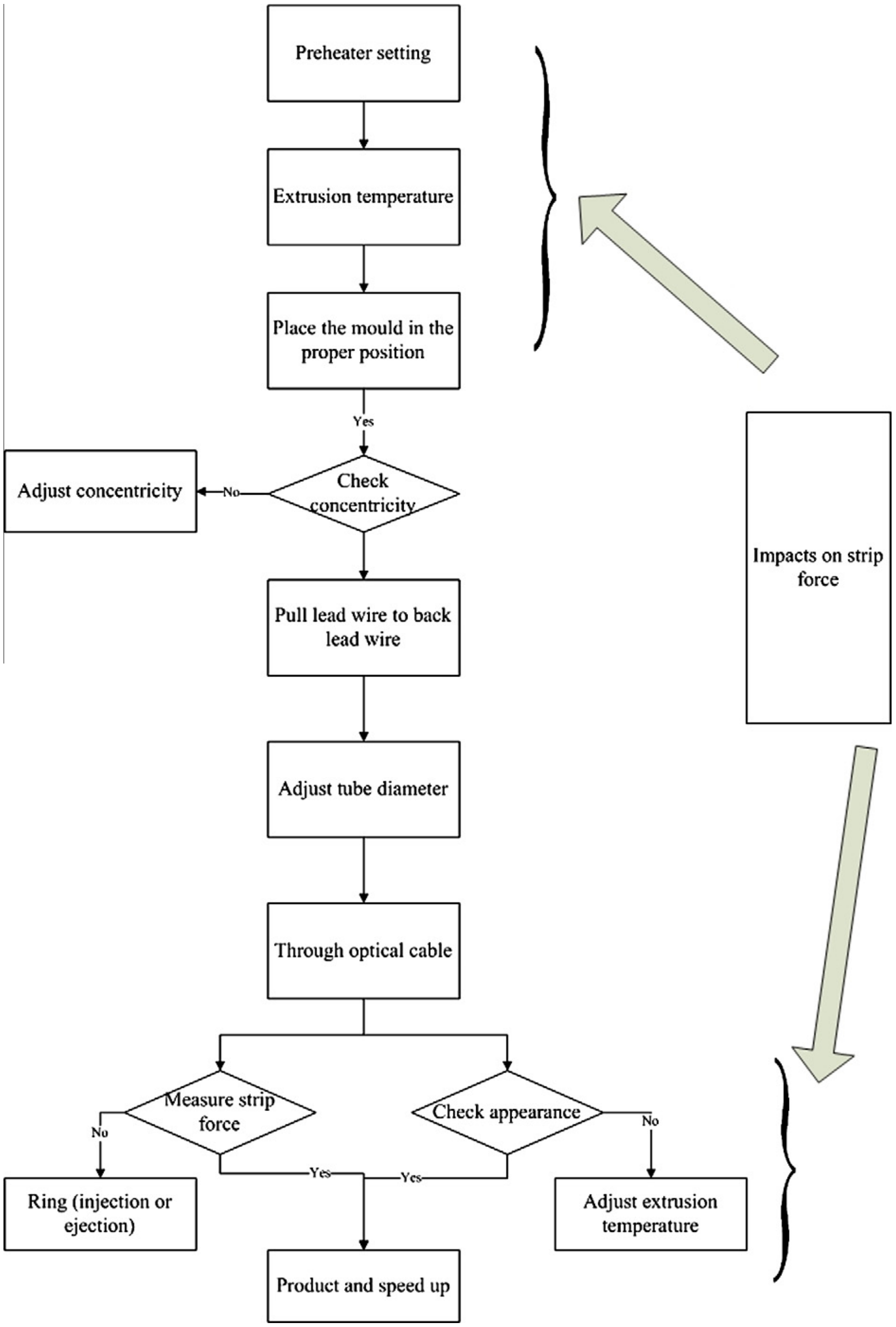

Fig. 3. Machine adjustment flow chart.

**Table 1**
Controlled factors and levels.

| Factor | Level | | |
|---|---|---|---|
| | Level 1 | Level 2 | Level 3 |
| (A) Pressure of machine head (bar) | 210 | 191 | 172 |
| (B) Extrusion temperature (machine head) (°C) | 190 | 173 | 156 |
| (C) Cooling water temperature (°C) | 44 | 40 | 36 |
| (D) Preheat temperature of optical fiber (°C) | 209 | 190 | 171 |

### 2.5. Control and discussion

The parameters design of the Taguchi method was used in experiments, and the results can be validated as correct upon validation testing and analysis of process capability. After process improvements are completed, maintenance work must be conducted. This study suggests the following controls:

(1) Change combination of factors, adjust pressure of machine head to 191 bar, reduce extrusion temperature of machine head from 173 °C to 156 °C, adjust temperature of cooing water to 40 °C, and reduce preheat temperature from 190 °C to 171 °C.
(2) Reestablish standardized control of tight sets of fiber according to modified factors combination, and make a control plan that incorporates testing and the application of strip force into a strict quality control system.

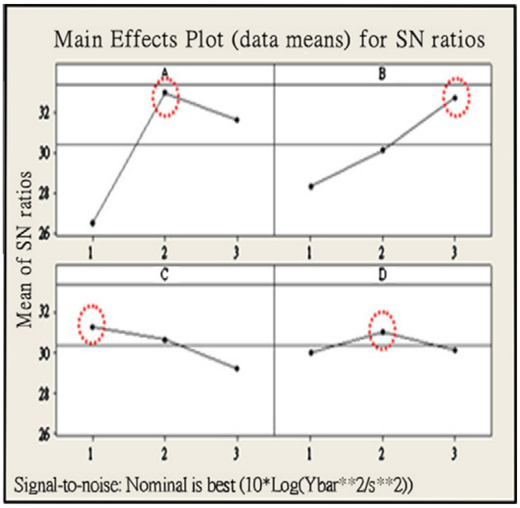

**Fig. 4.** Main effect for SN ratios.

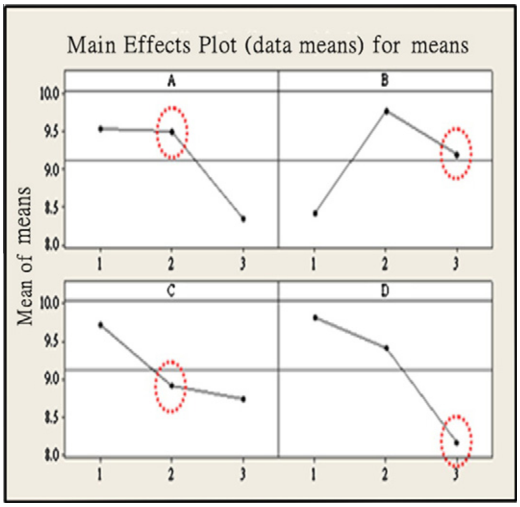

**Fig. 5.** Main effects for means.

(3) Continuously observe, record, and apply process capability analysis chart for monitoring, after process quality is stable, establish standard operational procedures (SOP) to facilitate operation of products development.

## 3. Conclusions and future study

This study applied IDEF0, Taguchi's Quality Engineering, and gray relational analysis to the measurement system of strip force tight sets of optical fiber in order to verify process capability improvements and minimize variations. This study investigated the processes for tight sets of fiber in a transnational optical connector manufacturer. It discussed detailed processes of tight sets of fiber during cladding, and suggested a workflow. In combination with Taguichi parameter design and ANOVA, optimal conditions can be inferred to improve quality of tight sets of fiber to meet customer demand. The improvement results indicated process capability $C_{PK}$ increased from 0.92 to 1.41, and demonstrated the process capability improvement model can effectively elevate quality stability of tight sets of fiber. It can be concluded that, the research model with IDEF0 modeling, the parameter design method of Taguchi's Quality Engineering, and gray relational analysis can systematically analyze and solve problems to improve product process capability [2,4,6].

In the future, the empirical analysis of product process capability and product quality improvement can be used to establish standard operational procedures defined by the process parameters of tight sets of fiber, and a management program for transnational optical connector manufacturers can be used to provide reference for quality improvement in the optical communication industry.

## Appendix A. Signal-to-Noise ratio (SN)

SN is designed to optimize the robustness of a product or process. The ideal SN ratio should include the following desirable features: the ability to reflect product quality variance, independent from the adjustment of average means (namely, SN ratio can predict quality upon target value changes); simplicity and additivity. The objective of robust design is to maximize predictable areas, while minimizing unpredictable areas [2]. Taguchi applied SN ratio to the statistics of communications engineering, and suggested that quality assessments use the approach shown:

$$SN = 10 \cdot \log_{10}\left(\frac{\text{Signal}}{\text{Noise}}\right) \tag{A.1}$$

When a signal factor is fixed, it becomes a static problem; therefore, SN ratio can be defined as shown in:

$$SN = -10 \cdot \log_{10}(\text{MSD}) \tag{A.2}$$

where MSD is the mean square deviation from the target value, and the SN ratio unit is dB.

SN ratio can be mainly divided into larger-the-better (LTB) SN ratio, smaller-the-better (STB) SN ratio, and nominal-the-best (NTB) SN ratio. This study used the NTB SN ratio, as shown in Eq. (A.3).

$$SN_{\text{NTB}} = 10 \cdot \log_{10}\left(\frac{\bar{y}^2}{s^2}\right) \tag{A.3}$$

$\bar{y}$ is the average of observed data; $s$ is the absolute value of the subtracted observed data.

**Table 2**
SN ratio variation analysis.

| Source | Degree of freedom | Sum of square | Mean square | *F*-value | *P*-value | Pure sum of square | Contribution rate (%) |
|---|---|---|---|---|---|---|---|
| A | 2 | 70.161 | 35.081 | 16.71 | 0.011 | 65.961 | 61.58% |
| B | 2 | 28.550 | 14.275 | 6.8 | 0.052 | 24.35 | 22.73% |
| C[a] | 2 | 6.375[a] | 3.188 | – | – | – | – |
| D[a] | 2 | 2.025[a] | 1.013 | – | – | – | – |
| Error | 0 | – | – | – | – | – | – |
| (Pooled error) | (4) | (8.4) | (2.1) | | | 16.8 | 15.69% |
| Total | 8 | 107.111 | | | | 107.111 | 100% |

[a] Represents insignificant impact factor.

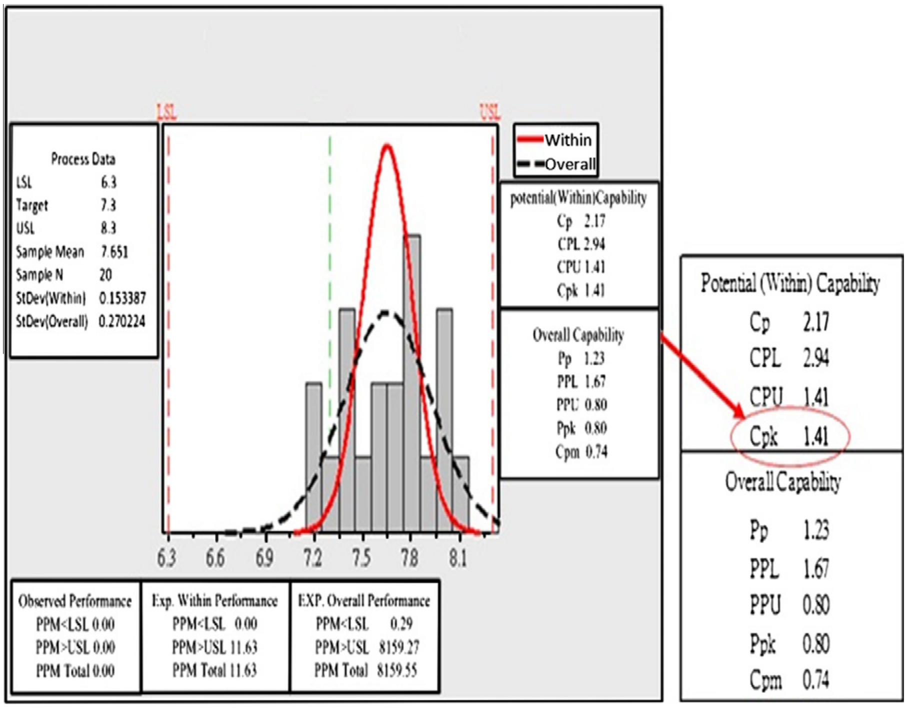

**Fig. 6.** Improved process capability analysis of tight sets of fiber.

## Appendix B. Integrated computer-aided manufacturing DEFinition (IDEF 0)

The IDEF family includes IDEF0 (Function Modeling), IDEF1 (Information Requirements Modeling), IDEF2 (Simulation Modeling), IDEF3 (Process Description Capture), IDEF4 (Object Oriented Design), IDEF5 (Concept/Ontology Description), IDEF6 (Design Rationale capture), and IDEF1X (Data Base Design). This study applied IDEF0 to the major descriptions of new product development in order to determine the optimal organizational activities, which are decomposed according to required details. This method is very effective at distinguishing between core organizational activities and secondary functions. The basic composition of IDEF0 presents activities in a box diagram, where four external arrows represent Input, Control, Output, and Mechanisms. Input refers to the raw materials and data necessary for the activity, Output refers to the products of the activity, Control refers to the restrictions and adjustments of the activity, and Mechanism refers to the resources required for the implementation of the activity. IDEF0 establishes the hierarchical model by the top-down method, by first selecting the model theme, followed by model viewpoints and objectives. The outermost diagrams are then constructed, on which the various sub-process diagram sequences are built. Finally, the descriptions of the construction documents are given [6,8].

## Appendix C. Process capability index ($C_{pk}$)

Kane proposed the concept of process capability index $C_{pk}$ [10], as shown in Eq. (C.1), and unilateral specification indices $C_{pu}$ and $C_{pl}$, as shown in Eqs. (C.2) and (C.3); where $C_{pk}$ is a combination of $C_a$ (Eq. (C.4)) and $C_p$ (Eq. (C.5)), which measures process concentrations and variance. Process capability index refers to the quality capability when the known process quality factors are controlled within a normal state. The process capability evaluation is shown in Table 3, which represents process accuracy and precision [9,10]. This study used $C_{pk}$ to measure process capability

**Table 3**
Process capability index. *Source*: [10].

| Level | $C_{pk}$ value | Quality status/management principles |
|---|---|---|
| A | $C_{pk} \geqq 1.67$ | Achieve quality standards and stable processes |
| B | $1.33 \leqq C_{pk} < 1.67$ | Achieve quality standards, with good process capabilities that can be slightly improved |
| C | $1 \leqq C_{pk} < 1.33$ | Process needs improvements |
| D | $0.67 \leqq C_{pk} < 1$ | Poor process capabilities require comprehensive review |
| E | $0 \leqq C_{pk} < 0.67$ | Advise to immediately halt production for comprehensive review |

$$C_{pk} = \min(C_{pu}, C_{pl}) = (1 - |C_a|) \times C_p \tag{C.1}$$

$$C_{pu} = \frac{USL - \mu}{3\sigma} \quad \text{(Upper specification only)} \tag{C.2}$$

$$C_{pl} = \frac{\mu - LSL}{3\sigma} \quad \text{(Lower specification only)} \tag{C.3}$$

$$C_a = \frac{|\mu - Target|}{(USL - LSL)/2} \tag{C.4}$$

$$C_p = \frac{USL - LSL}{6\sigma} \tag{C.5}$$

where *USL* is the upper limit of the specifications; $\mu$ the process average value; *LSL* the lower limit of the specifications; *Target* the median value of the specifications; $\sigma$ is the standard deviation.

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