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Analytical method for promoting process capability of shock absorption steel

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Abstract: Mechanical properties and low cycle fatigue are two factors that must be considered in developing new type steel for shock absorption. Process capability and process control are significant factors in achieving the purpose of research and development programs. Often-used evaluation methods failed to measure process yield and process centering; so this paper uses Taguchi loss function as basis to establish an evaluation method and the steps for assessing the quality of mechanical properties and process control of an iron and steel manufacturer. The establishment of this method can serve the research and development and manufacturing industry and lay a foundation in enhancing its process control ability to select better manufacturing processes that are more reliable than decision making by using the other commonly used methods.

Key words: Manufacturing performance index of shock absorption steel, *F* test statistic, Evaluation procedure, Process capability

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INTRODUCTION

There are many manufactured tools and products for daily use that are fabricated by iron such as: ironmongery, iron plate, iron strap, iron wire, iron stairs and other iron works. These products improve the living conditions of our life. To achieve the various use goals and give special functions to iron, other alloy elements are added into iron to produce alloy steel, used to manufacture cars, trains, motorcycles, machines, steel bridges, steel structures, etc. However, to achieve the different required purposes of a steel product, heat treatment procedure such as quenching and tempering can be used to increase the strength of steel. The key points of these production processes are the techniques of puddling and heat treatment after crushing. In order to promote the shock absorption capability of structures, new steel for construction are developed, such as: low yielding ratio steel, narrow yielding stress variation steel and low yielding stress steel (Chang *et al.*, 1997). Especially, mechanical properties of low yielding stress steel are suitable for producing metallic dampers (Bergman *et al.*, 1987; Dowrick, 1996). The precise and accurate mechanical properties of newly developed Low Yielding Strength Steel (LYS) must be strictly analyzed to produce the most suitable product for the use objective of shock absorption. The purpose of this research is to develop an analytical method for production management of LYS in the process of manufacturing to judge whether the mechanical properties meet the required standard or not.

This paper uses analysis and evaluation method of process capability of machinery made products to implement process control effectively in order to improve the manufacturers' ability of process control and mechanical properties estimation. Researchers who devoted studies to analysis and evaluation of process capability include: Kane, 1986; Chan *et al.*, 1988; Chou and Owen, 1989; Boyles (1991) Pearn *et al*., 1992; Boyles, 1994; Greenwich and Jahr-Schaffrath, 1995; Chen, 1998. Their research achievements included: satisfactory ratio of production process, loss function of production process and indices of production process capability. They are convenient and effective tools for evaluating the production process capability and performance based on the concept of the Taguchi loss function (Boyles, 1991), defined as $L(X) = (X - T)^2$. X stands for the characteristics of a certain product and T represents the target value. The quality loss of the product obviously is at minimum when $L(X) = 0$. Boyles (1991) pointed out that the expected value of the loss function represents process capability. The larger the value of process capability, the smaller the average loss and vice versa. A second time loss function was developed for calculating the difference between expected and tested tensile strength of LYS based on Taguchi loss function, with greater value indicating the tested tensile strength of LYS is higher than the expected tensile strength of LYS, which will result in lower low cycle fatigue. Insufficient yielding strength of LYS will occur if the tested tensile strength of LYS is smaller than the expected tensile strength of LYS. The paper employs this function to establish a best evaluation method for assessing the process capability and production management of low yielding strength steel in the manufacturing process.

EVALUATION FORMULA-MANUFACTURING PERFORMANCE INDEX OF SHOCK ABSORPTION STEEL

In the Taguchi Loss Function, T represents the tested tensile strength of low yielding strength steel (LYS) and E the expected tensile strength of LYS. When $X = T - E$, X is enhanced when the value is close to 0. In other words, the process control ability of LYS will depend on whether the tested tensile strength of LYS is higher or lower than the expected tensile strength of LYS. Thus, the difference between expected tensile strength of LYS E and tested tensile strength of LYS T should not exceed d the greatest tolerable value. We hope that the expected tensile strength of LYS can fall into the tolerable range (L, U). $U = T + d$ is the upper limit and $L = T - d$ is the lower limit. We use X^2 as the expected value since X could be a positive or negative value. The index for evaluating the process control ability of the manufacturing performance of shock absorption steel can be expressed as follows:

$$Loss = E(X^2) = (\mu_X)^2 + (\sigma_X)^2 \qquad (1)$$

It is obvious that this evaluation index *Loss* is similar to the Taguchi Loss function's (Kane, 1986) expected value. The closer the $(\mu_X)^2$ value is to 0, the more accurate the manufacturing ability and mechanical performance of LYS. When the value of the tested tensile strength of LYS is close to the expected value, a small value of $(\sigma_X)^2$ will be produced. High degree of accuracy and precision result from a smaller index value and the expected value generated. In order to accurately evaluate the manufacturing performance of LYS manufacturers, the natural evaluation method is proposed in this paper. The statistical inference is discussed as follows:

Iron and steel works can establish a smallest expected value of *Loss* based on the production management, process capability, technical staff and manufacturing control system. Sample X is a random variable since mechanical performance is affected by the tested tensile strength of LYS. Assume X_{i1}, X_{i2}, ..., X_{in}, $i = 1, 2$. The 1 and 2 of i symbolize different manufacturing process of LYS. The average values are μ_1 and μ_2 and variance values are σ_1^2 and σ_2^2. The normal distribution will be $X_1 \sim N(\mu_1, \sigma_1^2)$ and $X_2 \sim N(\mu_2, \sigma_2^2)$. The estimation is very accurate when the average value μ_i is close to the target value T. It is known that the target value should be 0, when the tested and expected tensile strength of LYS are the same. The smaller the σ_i^2 value is, the higher the degree of precision from the viewpoint of variance of estimation. The loss function of the manufacturing control capability of LYS is defined as:

$$Loss_i = \frac{3\sqrt{\sigma^2 + (\mu - T)^2}}{d} \qquad (2)$$

The loss function of the manufacturing control capability of LYS by natural evaluation method can be defined as follows:

$$\hat{Loss}_i = \frac{3\sqrt{S_i^2 + (\overline{X} - T)^2}}{d} \quad (3)$$

$\overline{X}_i = \left(\sum_{j=1}^{n_i} X_{ij}\right)/n_i$, $S_i^2 = (\sum_{j=1}^{n_i} X_{ij} - \overline{X}_i)^2/n_i$ represent the sample mean and variance of the assessed tensile strength for each manufacturing process of LYS.

d represents the greatest tolerable value of tensile strength of LYS. Table 1 summarizes the above-mentioned formulas.

Table 1 Sample data for the tested tensile strength of LYS

Sample	Average	Variance	Estimator
$X_1, \ldots, X_n$	$\overline{X} = \frac{\sum_{j=1}^{n_i} X_j}{n}$	$S^2 = \frac{\sum_{j=1}^{n_i}(X_j - \overline{X})^2}{n}$	$\hat{Loss}_i = \frac{3\sqrt{S^2 + (\overline{X} - T)^2}}{d}$

The probability density function of $\hat{Loss}$ (Vännman and Kotz, 1995) is

$$f_{\hat{Loss}_i}(x) = \frac{2^{1-n/2} C_i^n}{3^n x^{n+1}} \exp\left(-\frac{\lambda}{2} - \frac{C_i^n}{18x^2}\right) \cdot \sum_{i=1}^{\infty}\left\{\left(\frac{\lambda C_i^2}{36x^2}\right)^i \Big/ \left(i!\,\Gamma\left(\frac{n}{2} + i\right)\right)\right\}, x > 0 \quad (4)$$

where,

$C_i = \sqrt{n}d_i/\sigma$, $\lambda_i = \sqrt{n}(\mu_i - T)/\sigma_i$

Boyles (1991) and Pearn *et al*. (1992) stated that assuming normality $\sum_{j=1}^{n}(X_{ij} - T)/\sigma_i$ is distributed as non-central chi-square distribution with n degrees of freedom and non-centrality parameter λ_i. The r-th moment about zero of $\hat{Loss}_i$ is

$$E(\hat{Loss}_i)^r = \left(\frac{C_i}{3\sqrt{2}}\right)^r \cdot \sum_{j=0}^{\infty}\left\{\frac{e^{-\lambda_i/2}(\lambda_i/2)^j}{j!}\Gamma\left(\frac{n-r}{2} + j\right)\Big/\Gamma\left(\frac{n}{2} + j\right)\right\} \quad (5)$$

Particularly,

$$E(\hat{Loss}_i) = \left(\frac{C_i}{3\sqrt{2}}\right) \cdot \sum_{j=0}^{\infty}\left\{\frac{e^{-\lambda_i/2}(\lambda_i/2)^j}{j!}\Gamma\left(\frac{n-1}{2} + j\right)\Big/\Gamma\left(\frac{n}{2} + j\right)\right\} \quad (6)$$

$$E(\hat{Loss}_i)^2 = \left(\frac{C_i}{3\sqrt{2}}\right)^2 \cdot \sum_{j=0}^{\infty}\left\{\frac{e^{-\lambda_i/2}(\lambda_i/2)^j}{j!} \times \frac{2}{n + 2j - 2}\right\} \quad (7)$$

$$\text{Var}(\hat{Loss}_i) = E(\hat{Loss}_i)^2 - [E(\hat{Loss}_i)]^2 \quad (8)$$

The quantity $v_i(Loss_i/\hat{Loss}_i)^2$ is approximately distributed as chi-square distribution with v_i degrees of freedom, denoted by $\chi^2(v_i)$, where,

$$v_i = \frac{n_i(1 + [(\mu_i - T)/\sigma_i]^2)^2}{1 + 2[(\mu_i - T)/\sigma_i]^2}.$$

Since the process parameters μ_i and σ_i are unknown, v_i is also unknown, but can be estimated by calculating the values $\hat{v}_i$ from the sample. Where,

$$\hat{v}_i = \frac{n_i(1 + [\overline{X}_i - T)/S_i]^2)^2}{1 + 2[(\overline{X} - T)/S_i]^2}$$

EXAMINATION OF INDEX OF MANUFACTURING CONTROL OF LOSS

$Loss_i$ is an easy to understand and apply formula. The estimating ability can be determined by calculating the average value μ and variance σ^2 based on tested value and expected value of tensile strength of LYS. Tested value is computed according to the tested tensile strength of LYS. Therefore, this paper will make use and revise the nominally-the-best-type evaluation step of Chou *et al*. (1989).

1. Examination of index of control manufacturing of *Loss*

This paper will establish evaluation steps and standards based on the evaluation steps of Chou *et al*. (1989). Assume the null hypothesis and alternative hypothesis can be expressed as follows:

H_0: $Loss_1 = Loss_2$ (good ability to control manufacturing);

H_1: $Loss_1 \neq Loss_2$ (bad ability to control manufacturing)

Statistical evaluation formula can be expressed as follows:

$$F = \left(\frac{\hat{L}oss_1}{\hat{L}oss_2}\right)^2 \quad (9)$$

If $\hat{v}_i$ is used to estimate v_i, then $(Loss_i / \hat{L}oss_i)$ is very similar to $\chi^2(\hat{v}_i)/\hat{v}_i$. Statistical examination of F showed that it is similar to F-distribution with $\hat{v}_1$ and $\hat{v}_2$ degrees of freedom when $Loss_1 = Loss_2$. For level α test, assuming $F < F_{\alpha/2}(\hat{v}_2, \hat{v}_1)$ or $F > F_{1-\alpha/2}(\hat{v}_2, \hat{v}_1)$, null hypothesis is rejected and alternative hypothesis is favored. $F_\alpha(v_2, v_1)$ denotes the lower αth percentile of the F-distribution with v_2 and v_1 degrees of freedom.

2. Establish evaluation steps and standards

The method described above was examined statistically to evaluate the mechanical properties of LYS. Steps and standards are established here for clearer understand of the evaluation manufacturing process.

Step 1: Determine the α-risk (normally set to 0.05), thus revealing the chance of rejecting a true H_o.

Step 2: Take sample from each assessed tensile strength and calculate the sample mean $\bar{X}_i = (\sum_{j=1}^{n_i} X_{ij})/n_i$ and sample variance $S_i^2 = (\sum_{j=1}^{n_i} X_{ji} - \bar{X}_i)^2/n_i$ of suffix i, for $i = 1, 2$

Step 3: Calculate the values of $\hat{v}_i$, $\hat{L}oss_i$, and test statistically F, where

$$\hat{v}_i = \frac{n_i(1 + [(\bar{X}_i - T)/S_i]^2)^2}{1 + 2[(\bar{X}_i - T)/S_i]^2},$$

$$\hat{L}oss_i = \frac{3\sqrt{S_i^2 + (\bar{X}_i - T)^2}}{d_i},$$

$$F = \left(\frac{\hat{L}oss_1}{\hat{L}oss_2}\right)^2$$

Step 4: Decision rule:

(1) If $F_{\alpha/2}(\hat{v}_2, \hat{v}_1) \leqslant F \leqslant F_{1-\alpha/2}(\hat{v}_2, \hat{v}_1)$, then conclude $Loss_1 = Loss_2$.

(2) If $F < F_{\alpha/2}(\hat{v}_2, \hat{v}_1)$, then conclude $Loss_1 > Loss_2$.

(3) If $F > F_{1-\alpha/2}(\hat{v}_2, \hat{v}_1)$, then conclude $Loss_1 < Loss_2$.

CASE STUDY

A case study showed the applicability of this evaluation process. The mechanical properties of LYS are designed as 1). Yielding strength of LYS is only one third yielding strength of often-used steel A36, 2). Low cycle fatigue of LYS is 4.5 times that of often used steel A36. The tested results revealed that higher yielding strength of LYS resulted in lower low cycle fatigue. On other hand, the lower tensile strength LYS is not suitable for installation as metallic dampers and shock absorption accessories. In order to select better manufacturing process for LYS, the ratios, shown in Table 2, based on a mill report of the mechanical properties of the two steels were followed. Each numerical test represents the mechanical properties yielding strength of steel in each stove of different manufacturing process. The yielding strength of A36 steel is 36 kgf/mm^2. In order to avoid too much difference between tested yielding strength and expected yielding strength, the ratio of yielding strength of LYS and A36 is 0.333 and should not be exceed by more than 0.025. According to the provision of this specification, the target value T, the greatest tolerable value d, the upper limit U and the lower limit L are stipulated as 0.333, 0.025, 0.358 and 0.308 respectively.

Table 2 The tested values of different manufacturing process of LYS
(Ratio of yielding strength of LYS and A36)

Old manufacturing process				New manufacturing process			
0.353	0.323	0.363	0.378	0.332	0.341	0.336	0.343
0.333	0.335	0.354	0.364	0.331	0.323	0.349	0.338
0.375	0.368	0.337	0.351	0.343	0.336	0.353	0.328
0.321	0.331	0.341	0.339	0.326	0.343	0.327	0.349
0.313	0.322	0.376	0.361	0.319	0.336	0.319	0.325
0.355	0.315	0.361	0.341	0.349	0.328	0.328	0.348
0.367	0.343	0.323	0.334	0.355	0.327	0.329	0.327
0.320	0.351	0.337	0.361	0.329	0.348	0.367	0.355

The testing procedure is as follows:

Step 1: Determine the sample size $n_1 = n_2 = 32$ of each assess for different manufacturing process of LYS, with the significance level set at 0.05.

Step 2: From Table 2, calculate the values of $\bar{X}_1$, $\bar{X}_2$, S_1^2, and S_2^2, where

$$\bar{X}_1 = \frac{\sum_{j=1}^{n_1} X_{1j}}{n_1} = 0.01219,$$

$$\bar{X}_2 = \frac{\sum_{j=1}^{n_2} X_{2j}}{n_2} = 0.00709,$$

$$S_1^2 = \frac{\sum_{j=1}^{n_1} (X_{1j} - \bar{X}_1)^2}{n_1} = 0.110397,$$

$$S_2^2 = \frac{\sum_{j=1}^{n_2} (X_{2j} - \bar{X}_2)^2}{n_2} = 0.011788.$$

Step 3: Calculate the values of $\hat{v}_1$, $\hat{v}_2$, $\hat{L}oss_1$, $\hat{L}oss_2$, and the test statistically F, where

$$\hat{v}_1 = \frac{n_1(1 + [(\bar{X}_1 - T)/S_1]^2)^2}{1 + 2[(\bar{X}_1 - T)/S_1]^2} = 32.00464,$$

$$\hat{v}_2 = \frac{n_2(1 + [(\bar{X}_2 - T)/S_2]^2)^2}{1 + 2[(\bar{X}_2 - T)/S_2]^2} = 34.43373,$$

$$\hat{L}oss_1 = \frac{3\sqrt{S_1^2 + (\bar{X}_1 - T)^2}}{d_1} = 84.8896,$$

$$\hat{L}oss_2 = \frac{3\sqrt{S_2^2 + (\bar{X}_2 - T)^2}}{d_2} = 58.6391,$$

$$F = \left(\frac{\hat{L}oss_1}{\hat{L}oss_2}\right)^2 = 2.0956$$

Step 4: Calculate $F_{\alpha/2}(\hat{v}_2, \hat{v}_1) = F_{0.025}(34.43, 32.00) = 0.5044$, $F_{1-\alpha/2}(\hat{v}_2, \hat{v}_1) = F_{0.975}(34.43, 32.00) = 2.0037$.

$F > F_{\alpha/2}(\hat{v}_2, \hat{v}_1)$, then conclude $Loss_1 < Loss_2$. It means that the new manufacturing process is the better manufacturing process of LYS for the designed purpose and better than the old manufacturing process.

CONCLUSIONS

The ability to analyze the better manufacturing process of low yielding strength steel is a factor for deciding whether the production goal can be reached and whether the manufacturing processes can be proceed smoothly. This paper presents a method developed by authors for evaluating the better manufacturing process, and a method for evaluating the control capability of steel in the manufacturing process of an iron and steel works. Decision makers can quickly understand the analysis of the mechanical properties of LYS from the evaluation steps. Information can be utilized in process control for production improvement in the future.

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