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Robust Design Methodology for Sealing Performance of Gaskets

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Summary

This is the first attempt toward the development of robust design methodology applicable to gaskets as there is no such precedent in the sealing industry. This was achieved by drastically transforming the traditional approach toward the solution to leaking problem. This paper deals with a new all-metal gasket that incorporates strategically located circumferential annular lips that form seal lines with the flanges. The gasket, due to its special shape makes use of the material's spring effect, resulting in sealing performance. This approach is clearly distinct from the traditional one based on material development. By transforming a material development problem into one of mechanical design, we were able to optimize it using the Taguchi method. In FEM analysis, contact stress and deformation information was used to quantify leaking. Robust design methodology was developed and as a test case, a 25A sized industrial gasket was optimized using that methodology. Helium leak testing reveals considerable improvement in the sealing performance, hence verifying the applicability of the methodology developed.

Introduction

Elimination of asbestos from the Japanese sealing industry is proving to be an elusive goal. Despite government regulation banning all new use by year 2008, no suitable alternatives are forthcoming [1]. In this work, we deal with an all metal gasket, using an approach that is distinct from the traditional one based on development of new materials. This gasket incorporates strategically placed circumferential annular lips that, owing to the spring effect of the metal, form seal lines with flanges. This all important spring effect or elastic response is a function of material properties and physical dimensions of the gasket. Because sealing performance depends on this elastic response, material properties and physical dimensions of the gasket must be optimized for best performance. It is imperative that gaskets be designed to work not just in carefully controlled laboratory conditions but also in the rough plant environment. The objective thus, is robust design, which is immune or least sensitive to variations in environmental and operating conditions; as opposed to simple optimized design. Toward that end, and as a test case, we have optimized a 25A sized industrial gasket for sealing performance.

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Robust design by Taguchi method

Every engineered system is supposed to perform a specific task in response to a specific input (Fig. 1). A system consists of a combination of design parameters. Noise factors, in the form of variations in operating as well as environmental conditions, have a negative effect on the system, in that they tend to cause variation in output of the system. To achieve robust design, we need to set design parameters so that output is insensitive or least sensitive to noise factors.

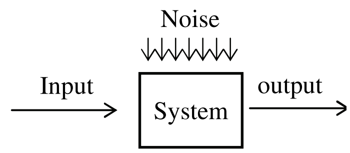

Figure 1: Engineered System

In Taguchi methodology, this is achieved by introducing noise factors into the design of experiments in a deliberate way. Once quantitative effects of these noise factors on system output are known, it is possible to figure out the most robust configuration.

In this problem, gasket corresponds to "system". This gasket is defined in terms of its design parameters. These design parameters are depicted in Fig. 2, which also shows the gasket cross section. Levels for physical dimensions were selected by engineering judgment, based on the original trial and error design. Two extremes of ordinary steel materials, in terms of yield strengths, were considered as candidate materials. Bolt preload corresponds to "input" – without satisfactory preload, sealing cannot be achieved. The noise factors are displayed in Table 1. In bolted flanged joints, the most critical noise factor is the variation in this preload. The unsafe-side figure for bolt preload (-10%) is based on empirical observations [2, 3] that suggest that even well maintained (lubricated) flanged joints, closed by effective bolt-up procedures can display variations up to ±10%.

Table 1: Noise factors

Noise factor	Level 1 Design level	Level 2 Unsafe-side
Bolt preload [kN]	33.4	30.0
Internal pressure [MPa]	20	22

We selected contact area along with contact stress [4] as the two criteria of evaluation (output). We supposed that higher values for both of these would result in higher sealing performance ("bigger is better" quality characteristic).

L_{18} and L_4 [5] orthogonal arrays were used for accommodating the design and noise parameters respectively. Thus in all, 72 FEM simulations were run. Optimization was performed for the two evaluation criteria independently and in parallel.

Design factors:
Material
Lip height h
Lip number
Pitch p
Overhang OH
Thickness t

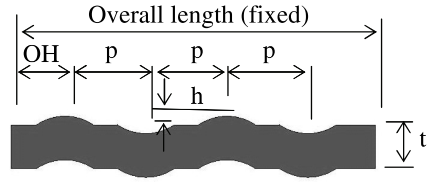

Figure 2: Gasket cross section and design parameters

For comparing the performance of the different design configurations, Taguchi method puts emphasis on SN ratio (S/N) as opposed to simple average of output. It is so because in order to achieve robustness, we must consider standard deviation instead of basing our decisions merely on averages. For bigger is better quality characteristic, S/N is calculated according to Equation 1:

$$S/N = -10 \log \left(\frac{1}{n} \sum_{n} \frac{1}{y_n^2} \right) \tag{1}$$

Finite element calculations were performed using the commercial code Ansys. Contact compatibility was enforced by using Augmented Lagrange algorithm, while sliding was controlled by Coulomb friction model.

Results and discussion

The data from FEM simulations was analyzed using regression analysis. Robust design can be picked directly from the S/N plots. Sensitivity analysis tells us about the effect of each design parameter on the robustness of the system. Both evaluation criteria (contact stress and contact area) yield same optimum design conditions for all design parameters except two (material and lip height), as shown in Table 2.

Table 2: Robust design levels

Design factor	Evaluation criterion	
	Contact stress	Contact area
Material	Mat 2	Mat 1
Lip height h [mm]	0.2	0.4
Lip number	2×2	2×2
Pitch p [mm]	3	3
Overhang OH [mm]	3	3
Thickness t [mm]	1.5	1.5

For experimental verification, precedence was given to robust design based on contact area because it is believed that a larger contact area is more beneficial because it can counter the roughness of contact surfaces. Figs. 3 and 4 show the

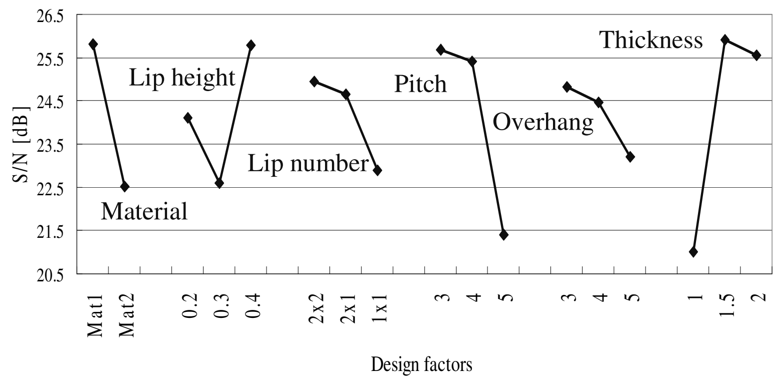

Figure 3: S/N plot: Contact area as evaluation criterion

S/N plot and results of sensitivity analysis for the evaluation criterion of contact area (contact length, since we performed 2D analysis).

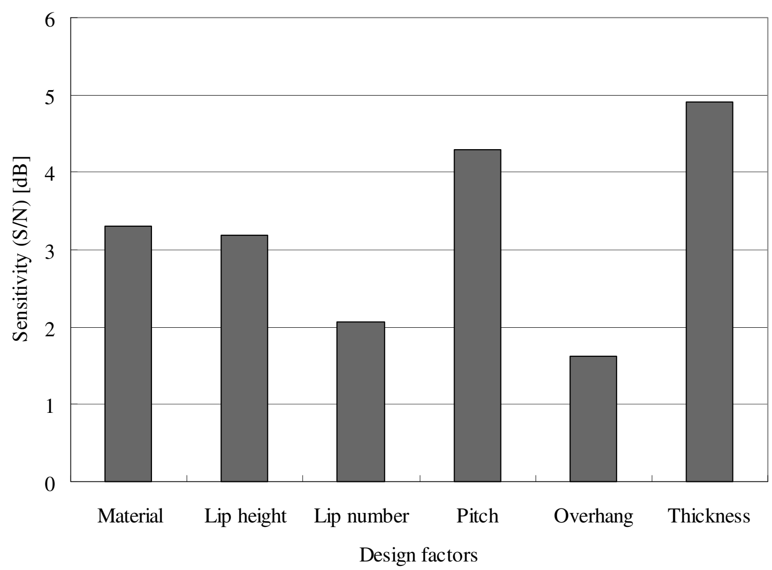

Figure 4: Sensitivity analysis: Contact area as evaluation criterion

Experimental verification

Experimental testing was performed for the quantitative evaluation of the optimization results. Helium vacuum test, as specified by JIS Z 2331 [6], was carried out for that purpose. The results of helium leak test, both before and after optimization, are shown in Fig. 5. "Before 1" and "Before 2" are two different designs based on variations of design variables in an arbitrary way.

"Robust design" is the design based on optimization performed by Taguchi method. It is evident that even at very low bolt preloads, the new design provides a

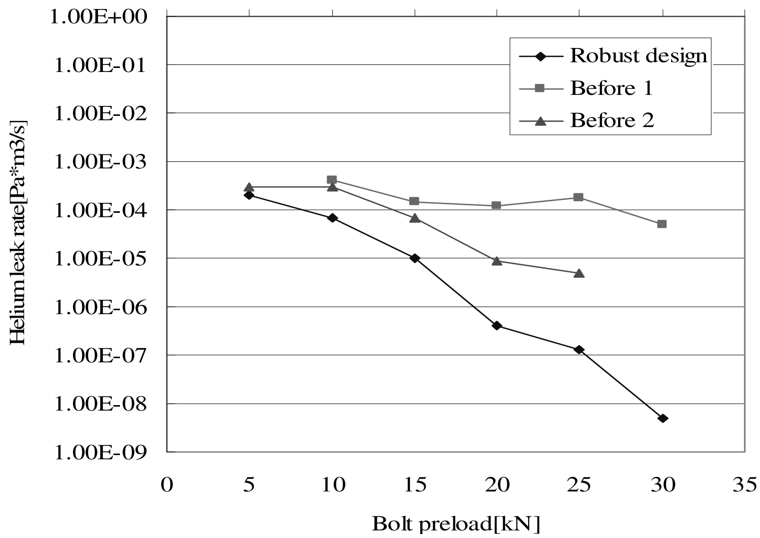

Figure 5: Results of helium leak test

marked improvement on the original trial and error designs, with leaking rate lower than 1E-08 Pa·m^3/s.

Conclusions

Detailed design methodology for robust design of a new all-metal gasket was developed. As a test case, the design of a 25A sized industrial gasket was optimized. Helium leak test results reveal considerable improvement in sealing performance, thereby verifying the methodology developed. It is hoped, therefore, that the methodology developed here can be successfully extended to sizes other than 25A.

This has been the first instance of an attempt at robust design of a gasket, as there is no such precedent in the sealing industry. This was made possible by transforming the problem from material research and development to one of mechanical design. Results make it abundantly clear that material development is not the only approach towards the development of new, more effective gaskets.

The effectiveness of Taguchi method to the problem of leaking has also been verified. Taguchi methodology was utilized for designing FEM simulation runs. These simulations were effective in predicting the leaking performance, even though FEM cannot deal with the phenomenon of leaking directly. This was done by careful selection of evaluation criteria. Contact area has been shown to be the most important evaluation criterion for gaskets of this type. Effectiveness of FEM simulations reduced the number of real hardware tests drastically.

Acknowledgement

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