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Statistical tools applied for the reduction of the defect rate of coffee degassing valves

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ABSTRACT

Coffee is a very common beverage exported all over the world: just after roasting, coffee beans are packed in plastic or paper bags, which then experience long transfers with long storage times. Fresh roasted coffee emits large amounts of CO_2 for several weeks. This gas must be gradually released, to prevent package over-inflation and to preserve aroma, moreover beans must be protected from oxygen coming from outside. Therefore, one-way degassing valves are applied to each package: their correct functionality is strictly related to the interference coupling between their bodies and covers and to the correct assembly of the other involved parts. This work takes inspiration from an industrial problem: a company that assembles valve components, supplied by different manufacturers, observed a high level of defect rate, affecting its valve production. An integrated approach, consisting in the adoption of quality charts, in an experimental campaign for the dimensional analysis of the mating parts and in the statistical processing of the data, was necessary to tackle the question. In particular, a simple statistical tool was made available to predict the defect rate and to individuate the best strategy for its reduction. The outcome was that requiring a strict protocol, regarding the combinations of parts from different manufacturers for assembly, would have been almost ineffective. Conversely, this study led to the individuation of the weak point in the manufacturing process of the mating components and to the suggestion of a slight improvement to be performed, with the final result of a significant (one order of magnitude) decrease of the defect rate.

1. Introduction

Coffee is nowadays a very common beverage all over the world. The best way to taste it is to have it prepared from freshly roasted beans. Trade is usually conducted by Multinational companies that export coffee in many countries all over the world. Just after roasting, coffee beans are packed in plastic or paper bags. Afterwards, the procedure for exporting is started, involving very long transfers and long storage times (before departure, passing the border, upon arrival). Coffee beans may generally be conserved even for a long time, but three important issues must be considered [1]. Fresh roasted coffee beans are responsible of the emission of large amounts of gas (CO_2): this process starts just after roasting and may last for up to several weeks. Retaining these gases inside the package may be dangerous, as it may cause package inflation with

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consequent failure. Moreover, inflated packages may also roll over the shelf and then drop down to the floor. The second issue is related to the importance of preventing the escape of the high molecular weight gases, constituting the product's aroma [2]. The final issue to be considered is that coffee requires protection from oxygen to maintain its fresh roasted taste. Oxygen has a chemical reaction with the volatile flavors in fresh roasted coffee, causing its quick degradation. Therefore, it is important to warrant an efficient sealing from the external environment, to prevent oxygen flow toward the coffee beans

In order to meet the aforementioned requirements, coffee one-way degassing valves were developed and introduced into market. Nowadays, they are largely produced: their function is to preserve roasted coffee flavor before its consumption: some images are shown in Fig. 1. Their important role at warranting the high quality and taste of coffee beverages, along with their chemical properties to be conserved during storage, is emphasized in some recent studies [3,4]. The valve consists of a body, directly attached to the package, and supporting a rubber disk and a filter.

Their functions are respectively to provide an oxygen-proof seal and to prevent small particles from clogging the one-way valve. They are finally fixed by a plastic cover with a small hole for air exhausting. A scheme of the valve is shown in Fig. 2(a), along with details regarding the coupling dimension of the valve body and the cover in Fig. 2(b). The connection between the two parts is theoretically warranted by the interference between the inner cylindrical surface of the body and the external one of the cover. In [1] it is reported that many roasters are experiencing an unacceptable oxygen exposure, with consequent degradation of the product. Every single valve has a very low economic value (less than 1 $), however a widespread malfunctioning may lead to a significant economic loss, due to poor quality of the traded coffee. Despite the serious outcomes from not conformal or failing degassing valves, to the best of the author's knowledge, this issue has never been tackled in literature. In particular the typical tools of statistics and reliability have never been applied as a rigorous approach to control the defect rate. This occurrence is the main motivation of this research.

The present paper takes inspiration from an industrial case study. A company that manufactures coffee valves, assembling components from different suppliers, observed a high defect rate, considering own quality control and after sales costumer remarks. The defect rate was around 4%, considering a year production of over 200,000 valves.

The aims of this study can be summarized in the points below:

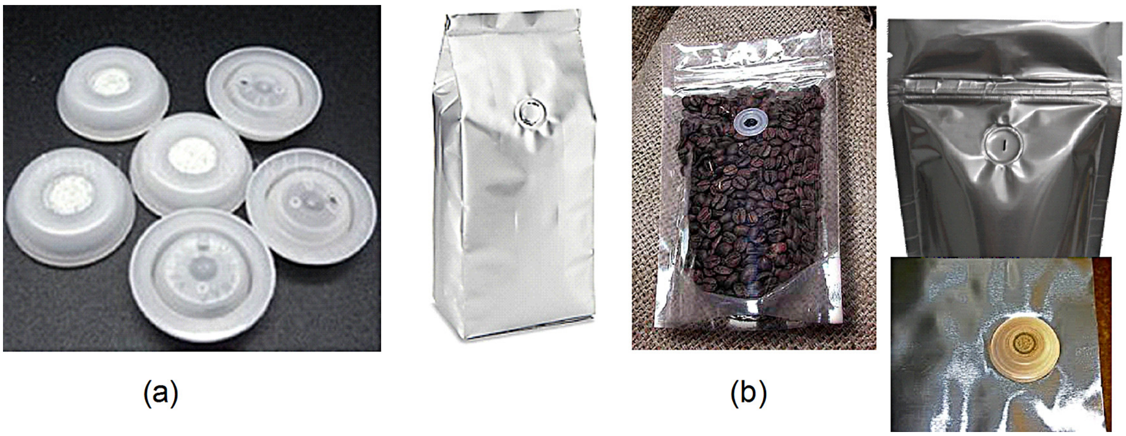

Fig. 1. Coffee valves (a) just after assembly and (b) upon their application to the package.

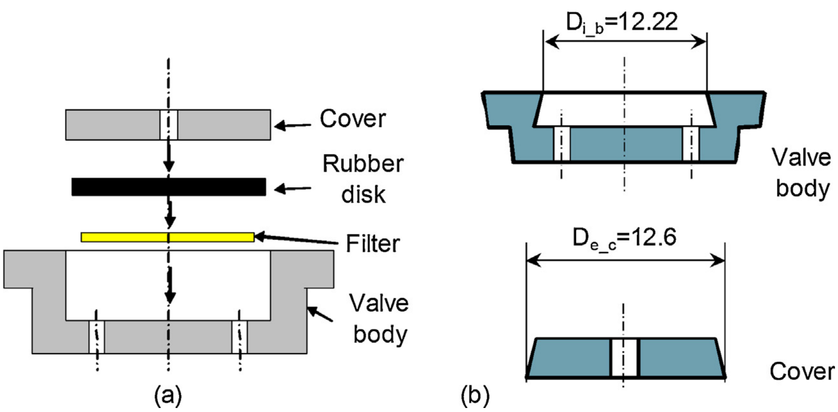

Fig. 2. (a) General scheme of the valve, (b) sketches of the valve body and of the cover with related coupling dimensions (dimensions in mm).

- Investigating the causes of this high defect rate.
- Creating a tool for the prediction of the defect rate.
- Processing the possible strategies to reduce the defect rate.

2. Quality tools applied for the investigation of the failure causes

The investigation regarding the causes for the frequent failures involving the manufactured valves was initially tackled by the tool of the Pareto chart. Its adoption was able to yield a resume of the different failure modes and of their level of occurrence. A similar approach was used in [5], where cake diagrams were developed to collect the different failure modes, involving steel coils before and after manufacturing process improvement. Afterwards, the technique of the Fault Tree Analysis (FTA) [6] was applied for the top-down analysis from the failure event to the primary reasons for each failure mode. Finally, the tool of the Failure Mode and Effect Analysis (FMEA) [7] was utilized to infer the effects of the failure modes, evaluating and scoring their frequency of occurrence and detectability. The computation of the Risk Priority Number (RPN) made finally possible to find out the most critical failure mode. In particular, the FTA and the FMEA are regarded in literature as powerful tools in engineering failure analysis to eliminate potential failure sources [8,9]. For instance, in [10] FMEA and FTA were jointly used for an efficient failure analysis of a coffee maker. The FTA was used in [11] to investigate the failure occurrence probability in a cement plant. The Pareto chart and the FTA are shown in Fig. 3, whereas the FMEA output is shown in Table 1, where S, O, and D respectively stand for Severity, frequency of Occurrence and Detectability. The scores are in the range 1–10 and have been assigned, following the recommendations in [12]; the occurrences in the Pareto chart have been weighted, considering the estimated total defect rate.

According to the performed analysis, the most critical failure mode seems to be related to body and cover tending to get disassembled during the following use. This type of failure, due to an insufficient interference between the valve body and the cover, is presumably induced by vibrations during transfers or by the process for valve application to coffee bags. Over the 80% of failures occurred, according to this mode, moreover the RPN (yield by S·O·D) is further increased by the severity of the effects and the quite difficult detectability unless a specific control, time consuming and expensive, is performed by the manufacturer, usually by means of a shaker. Therefore, the further analysis was focused on the failure mode of decoupling by lack of interference.

Considering the drawing in Fig. 2, the body has a nominal inner diameter D_{i_b} of 12.22 mm, whereas the cover has a nominal external diameter D_{e_c} of 12.6 mm. Therefore, the level of interference is theoretically quite high: 380 μm. An important question is related to the minimum threshold of interference to prevent decoupling. Empirical tests, where a number of just assembled valves was posed into a vibrating box, to study the efficiency of the assembly, led to the conclusion that the aforementioned threshold is around 80 μm. Beyond this value the assembly may be regarded as safe. However, the first issue to be observed was that serious problems may arise from the manufacturing process of these components. Both the valve body and the cover are made of Polyethylene by injection molding with the use of 24-cavity molds. This process requires a rake angle of approximately 10°, visible in Fig. 2(b) and prevents from accomplishing strict coupling tolerances. Final part dimensions may be affected not only by the strictly controlled cavity geometry, but also by wear, temperature and cooling time. A further issue that made the question more complicated was that the same parts, the body and the cover, were produced by two different manufacturers, due to the high number of pieces required for production.

3. Experimental sampling: results and statistical analysis

In order to investigate in more details the failure mode caused by insufficient interference at the coupling, an experimental campaign was set up to determine the statistical distributions of the coupling dimensions of both components, considering the pieces released from the two different suppliers. Indicating the two manufacturers (man.s) as A and B, two populations of N = 80 valve bodies from both were considered. A sample size of 80 pieces was chosen according to [13], since this can be regarded as a proper size to retrieve a reliable statistical distribution. At the same way, two additional 80-piece sized populations of covers from man.s A and B were involved in the dimensional analysis. The coupling dimensions (see Fig. 1) D_{i_b} and D_{e_c} were determined for each component by a profile projector, having a resolution of 2 μm. The results were then statistically processed in order to determine the distributions of the studied dimensions, together with their mean values and standard deviations. In particular, the optimal number of categories (N_c) was determined according to Eq. (1) (available for instance in [13]), where *Log* stands for 10 base logarithm: therefore, 7–8 categories were used.

$$N_c = 1 + 3.3 \cdot Log(N) \quad (1)$$

The results were then collected into four histograms: two samples are shown in Fig. 4(a), with reference to the valve body internal diameter, where the densities are plotted vs. the dimensional ranges. The tool of the Normal probability plot, in particular the quantile–quantile plot, was used to check the suitability of the Normal distribution in the description of the data. The normal probability plots retrieved for the dimensional distributions in Fig. 4(a) are shown in

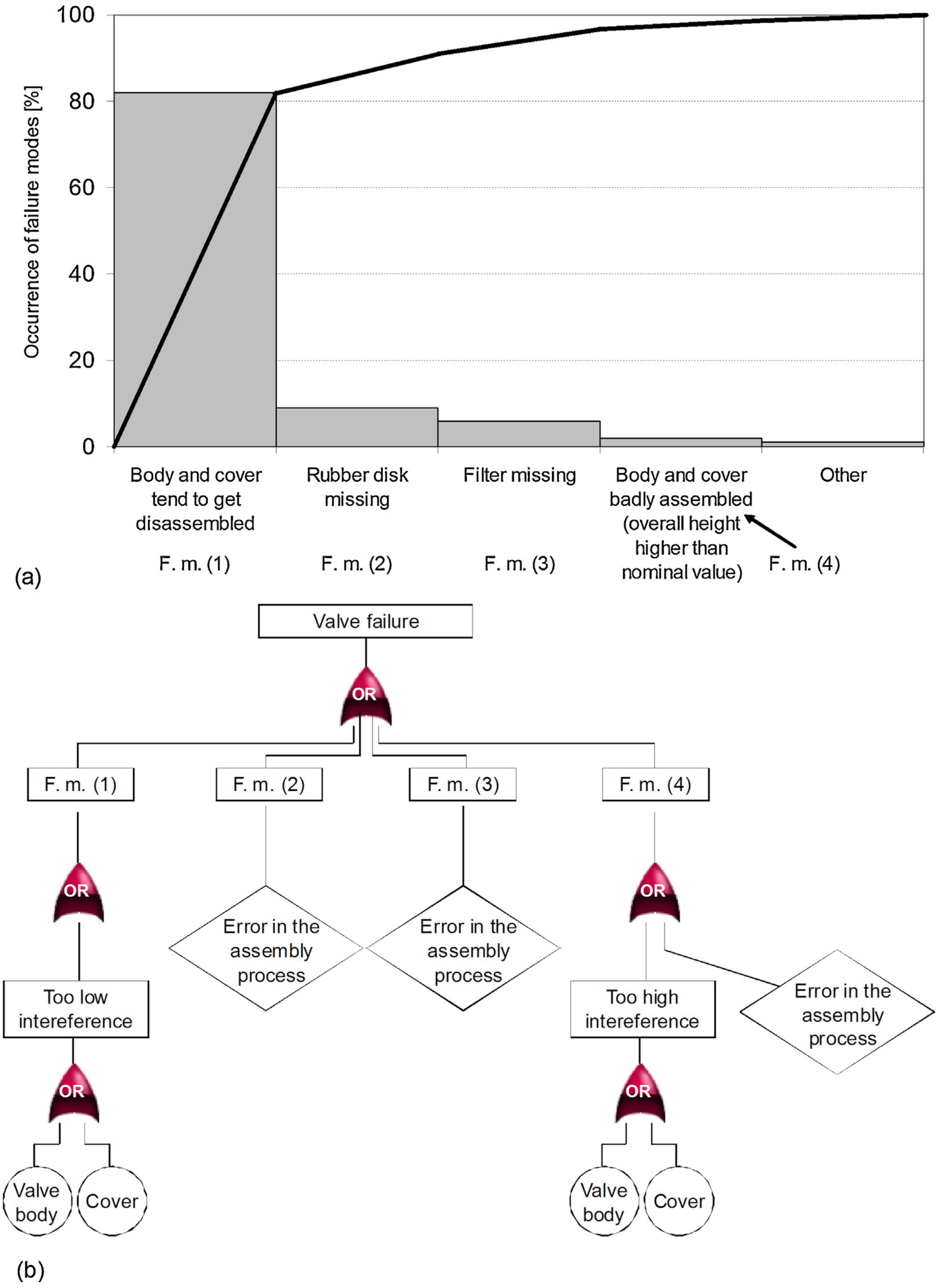

Fig. 3. (a) Pareto chart and observed failure modes (F. m.s), (b) Fault Tree Analysis (FTA) and research of the failure sources.

Fig. 4(b). In these diagrams each measured dimension is dot-by-dot plotted vs. the related quantile, determined according to [13]. The linear trend, as testified by the very high value of the linear correlation coefficient R^2 (also reported in the graph), justifies the use of a Normal distribution to interpolate the data [13]. Following this outcome, the computation of the mean values and of the standard deviations of the data populations led to the determination of the four Normal distributions of the coupling dimensions. Considering the valve body internal diameters, probability density functions (pdfs) are also appended to Fig. 4(a), whereas the means (μ) and the standard deviations (σ) are collected in Table 2.

Table 1
Failure Mode and Effect Analysis (FMEA) and criticality of the failure modes (F.m.s).

Failure mode (F. m.)	S		O		D		RPN
	Comment	Score	Comment	Score	Comment	Score	
F. m. (1)	Not working at all	10	Insufficient interference in the coupling	9	Can be checked only by tests on a shaker	5	450
F. m. (2)	No oxygen seal	10	Error in the assembly process	6	Easy to check	1	60
F. m. (3)	Risks being clogged	8	Error in the assembly process	6	Easy to check	1	48
F. m. (4)	Impossible to be applied to the package	10	Error in the assembly process or too high interference	4	Easy to check	1	40

4. Predicting the defect rate by statistical methods

As mentioned in the Introduction Section, a further aim of this study consisted in the development of a numerical tool for the prediction of the defect rate. This question was tackled, combining the experimentally retrieved data of the statistical distributions, and considering the basic formula that yields the interference level between the two mating parts. Regarding the first issue, it must be pointed out that, according to several papers [11,14–18] in literature, reliability assessments are necessary to manage the variability or the scattering of the input data and to determine their effect on the dispersion of the result. The preliminary step for processing this variability usually consists in the performed statistical analysis [15–17,19–27], described in the previous section. The second issue, the computation of interference, can be easily tackled by the implementation of Eq. (2), where Int. stands for the interference level.

$$Int. = D_{e\_c} - D_{i\_b} \tag{2}$$

Considering that D_{e_c} and D_{i_b} are random variables with known Normal distributions, the problem stands in the determination of the distribution of the output variable. According to several references, such as [13], the Interference level, being a linear combination (difference) of normally distributed inputs, may also be regarded as a normally distributed variable.

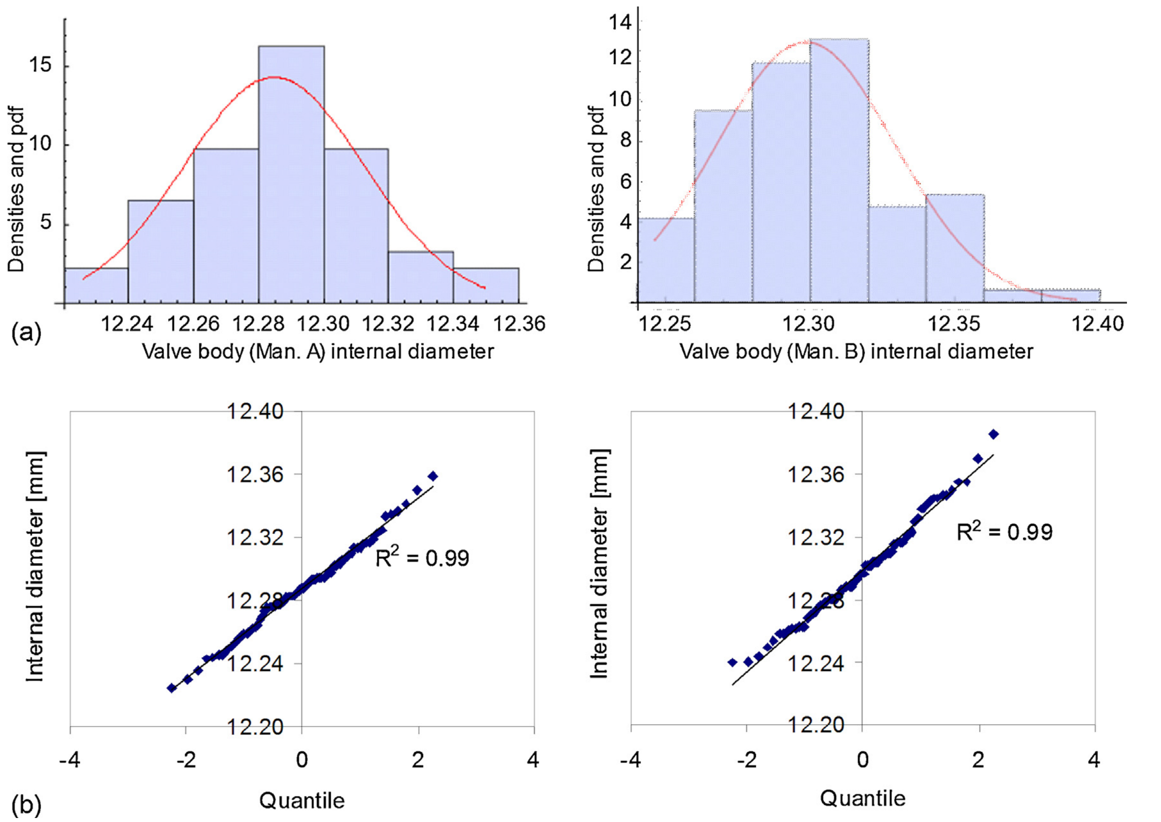

Fig. 4. Two examples (valve body internal diameter by manufacturers A and B) of the determined distributions for the coupling dimensions and (b) related normal probability plots.

Table 2
Mean values and standard deviations (all values in mm) of the valve body and cover coupling dimensions by the manufacturers A and B.

	Man. A		Man. B	
	μ	σ	μ	σ
V. body	12.284	0.029	12.298	0.030
Cover	12.441	0.030	12.467	0.044

Table 3
Four different coupling combinations, considering valve bodies and covers from manufacturers A and B.

		Cover	
		Man. A	Man. B
Valve body	Man. A	Case A-A	Case A-B
	Man. B	Case B-A	Case B-B

Its mean value and standard deviation, respectively $\mu_{Int.}$ and $\sigma_{Int.}$ are easily yield by Eq. (3) and Eq. (4), respectively [13].

$$\mu_{Int.} = \mu_{D_{e\_c}} - \mu_{D_{i\_b}} \tag{3}$$

$$\sigma_{Int.} = \sqrt{\sigma^2_{D_{e\_c}} + \sigma^2_{D_{i\_b}}} \tag{4}$$

In these equations σ^2 stands for the variance, that is, the square of the standard deviation σ. Moreover, the subscripts D_{e_c} and D_{i_b} are appended to indicate the variables, for which the mean value, the standard deviation or the variance are considered.

The described procedure was repeated for all the possible body – cover combinations listed in Table 3, thus computing the mean value and the standard deviation of the Interference output variable in the four cases A-A, A-B, B-A and B-B. For instance, the aforementioned values, $\mu_{Int.A\text{-}B}$ and $\sigma_{Int.A\text{-}B}$, are respectively, yield by Eq. (5) and Eq. (6) for the A-B combination.

$$\mu_{Int.A-B} = \mu_{D_{e\_c}B} - \mu_{D_{i\_b}A} \tag{5}$$

$$\sigma_{Int.A-B} = \sqrt{\sigma^2_{D_{e\_c}B} + \sigma^2_{D_{i\_b}A}} \tag{6}$$

Subscripts A and B are appended to the diameter input variables, to denote the two manufacturers. Presuming a Normal distribution, the four cumulative distribution functions (cdfs) were therefore determined. Monte Carlo simulations (one for each of the cases in Table 3), accounting for the distributions of the coupling dimensions, were finally performed to check the retrieved distributions. The cdfs are plotted together in Fig. 5, where the interference level along the horizontal axis ranges up to 100 μm. As it is well known, the cdf, computed for a generic value of interference, returns the probability of the real interference being below that value. Therefore, if the generic value is regarded as an interference threshold, below which the valve body and the cover are likely to get disassembled, the computed probability may be regarded as a probability of failure and as an estimate of the defect rate. The empirically determined interference threshold of 80 μm is highlighted in Fig. 5.

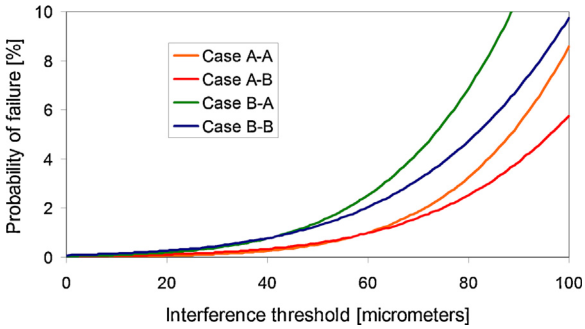

Fig. 5. Probability of failure plotted vs. the interference threshold in the current conditions.

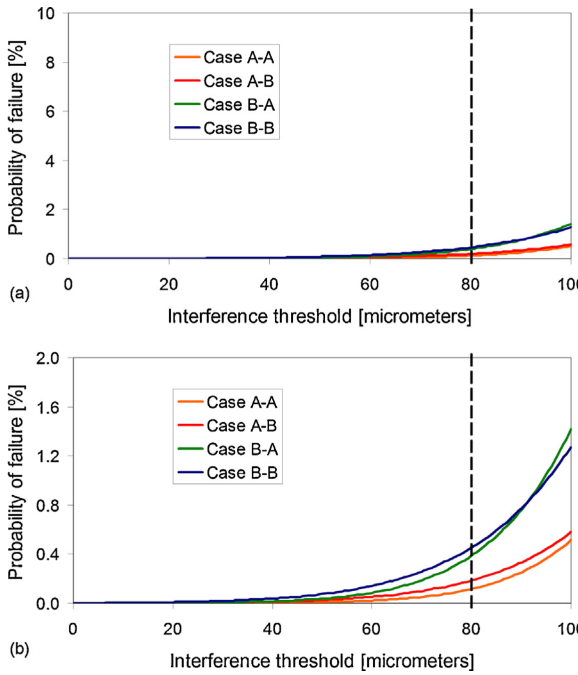

Fig. 6. (a) Probability of failure plotted vs. the interference threshold for a 0.05 mm incremented cover diameter, same scale of Fig. 4; (b) zoomed view of the same graph.

5. Discussion: how to reduce the defect rate

Considering the outcomes of the statistical analysis and the results in Table 2, it can be remarked that the averaged values are generally far away from the nominal ones. The highest discrepancies affect the external dimensions of the covers (D_{e_c}), which are more than 0.1 mm lower than the required value. It is indeed one of the causes of bad coupling. Another issue to be remarked is related to the much higher standard deviation of the cover dimensions, considering manufacturer B.

Examining then the defect rate predictions in Fig. 5, it is interesting to observe that the averaged value, calculated considering the threshold of 80 μm, 4.3%, is very close to the observed rate in production.

At the beginning of this study, an open question was whether the defect rate could be lowered, specifically requiring to connect parts from the same supplier (couplings A-A and B-B of Table 3). Conversely, the analysis of the curves in Fig. 5, leads to the outcome that the best coupling is A-B, for which the predicted defect rate is just 2.5%. Of course, the need of making use of all the bodies and all the covers by both manufacturers, would lead to the choice of a crossed coupling strategy, that is, connecting the body by supplier A to the cover by supplier B and vice versa. However, the predicted defect rate for the B-A coupling is unfortunately the highest (6.9%). An average of these two values leads to an expected failure rate for the entire production of 4.7%, even greater than the actual one. Therefore, the strategy of connecting parts from the same manufacturer seems to be acceptable, even if it is just a compromise: the defect rate in this case (average between the two intermediate values) is 3.9% with a slight and presumably not significant improvement of quality.

Therefore, the conclusion of this analysis was that it was not possible to achieve a significant improvement, just requiring a particular strategy, when coupling parts.

It has been pointed out that the covers by manufacturer B exhibited a higher scattering, but this occurrence seems not to have a strong impact on production. Conversely, the most detrimental effect, increasing the defect rate, seems to be related to the not conformity of the covers, whose external diameters are much lower than requirements. The simple model in Eq. (3) was applied again, to determine the impact of a just 0.05 mm increment (with respect to the actual mean value) of the dimension D_{e_c} (presuming that the standard deviation remains unchanged), which could be easily fulfilled by a better control on the parameters of the injection molding process, without modifying the cavities. The curves plotted in Fig. 6 retain the same meaning as those in Fig. 5: it can be easily observed that the expected rates are in this case much lower, with a decrease of about one order of magnitude.

6. Conclusions

A problem of high defect rate in the production of coffee valves was tackled, using first the basic tools of quality design and performing a dimensional analysis of the involved parts. Subsequently, a statistical analysis of the data, led to the determination of their distributions. Afterwards, an easy approach was proposed, to indicate the most suitable strategy to improve production quality, predicting the achievable defect rate. A specific requirement addressed to the suppliers led to more conformal dimensions of the covers, with the final result of a significant decrease of the defect rate to acceptable values.

Acknowledgements

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