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Application of the design of experiments and statistical hypothesis to reduce defects in the flange of the steel plate process

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Abstract

The paper presents a discussion on the occurrence of defects in the circumferential flange of steel plate. The numerous flange face defects have been analysed. The types of defects have been selected and categorized using an experimental planning procedure involving 600 samples for 24 different process variants, considering variables such as material, hole diameter, tool size and tool position. The analysis of experimental results enabled to determine of the optimal values of process parameters to minimize the occurrence of defects. Furthermore, the influence of individual parameters on the quality of the flange surface has been carried out to obtain the process parameters' impact using statistical hypotheses. As a result, it was possible to develop rules which will be helpful in the design process, especially important when changing the material to be processed.

Keywords: laser cutting, flanging, fracture, statistical hypotheses

1. Introduction

Hollow products with flanges find many technical applications. They are widely used in the engineering and aerospace industries, as well as in automotive, agriculture, construction as transmission shafts, centring sleeves, bushings connecting two shafts, balustrade elements, gears, etc. The collars are usually applied to provide additional support for press fits for bolts or to provide greater area for soldering in connection with tubes for thread cutting. Depending on the purpose, these products have a different structure, ensuring that the required tasks are met during their operation. The combined flanges are manufactured thanks to the use of various types of joining techniques and materials, both inseparable (e.g., welding) and disjointed (e.g., twisting), while monolithic flanges are possible to obtain thanks to the use of plastic processing, casting, and machining (Gontarz & Winiarski, 2015).

The paper's main goal is to discuss how sheet metal forming process parameters influence the occurrence of defects. For this purpose, the flanged component produced using the circumferential collar flanging process has been presented. This technology uses a sheet blank with a hole to punch it into a die and to form a hollow-flanged piece, commonly with a blank holder around its periphery. The greatest strains are in the periphery of the expanded hole, i.e., the major deformation increases the diameter of the initial hole while the wall thickness is reduced. However, the tensile stress

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in the circumferential direction at the edges of flanged holes is the main cause of failure due to cracking or tearing (Moneke & Groche, 2018; Samołyk, 2012).

This article presents a solution to the engineering problem of the unacceptable cracking of flanges in the production process. For this purpose, the authors used the design of experiment methodology, which is widely used in the determination of parameters of technological processes (Bober, 2017; Grzegorzewski & Kochański, 2019). The impact of selected process parameters on defect occurrence has been examined thanks to numerous experimental tests. The defect classification system was proposed due to the fact that the part is to be manufactured with the tolerance imposed by the customer. Thanks to this, the results obtained in the test could be analysed in terms of determining optimal parameters due to minimizing the occurrence of a critical defect level. However, thanks to conducting additional analysis using various statistical hypotheses, several theses were formulated and tested that could expand engineering knowledge regarding the production of flanged parts.

The component described in the paper is a part of the Faurecia S.A. production in Grójec, Poland, manufactured as a part of the car seat guide, and its key feature is the flange surrounding a hole of a set diameter (Fig. 1a, b). The cracking occurs at the perimeter of the flange (Fig. 1c) as an irregular defect. The industry requirements, closely related to the strength conditions of the car seat, exclude the use of a component with such defects in the final product. Even a small local thinning of the collar, not to mention cracking, are able to significantly reduce the durability and strength of the connection of the seat guide with the car floor, which directly affects the safety of people in the vehicle.

The manufacturing process of the described part with a flange consists of several operations (Fig. 2). The first one is laser cutting of the outer shape and the hole, followed by reaming and chamfering of the hole intended to be the top of the flange (Fig. 2a). These operations are necessary to obtain a sufficient quality of the hole to create a flange with the expected quality of the edges. The blank was cut using a laser with a beam power of 2600 W and with a companion gas pressure (oxygen) of 0.7 bar. Chamfering of the hole was carried out on the same drill and milling machine on which the hole reaming operation is performed, using the same die and a countersink with a diameter ⌀10.2 mm and an angle of 90°. Chamfering is carried out on one side of the hole and the other to a depth of 1 mm ±0.1 mm. The flange forming operation (Fig. 2c) is preceded by bending the side edge of the workpiece (Fig. 2b). To obtain the dimensions imposed by the technical documentation, a flange calibration operation is necessary to ensure the required geometry and tolerances (Fig. 2d). Calibration is not only aimed at obtaining the set height of the flange but also at eliminating possible irregularities at its edge.

a) b) c)

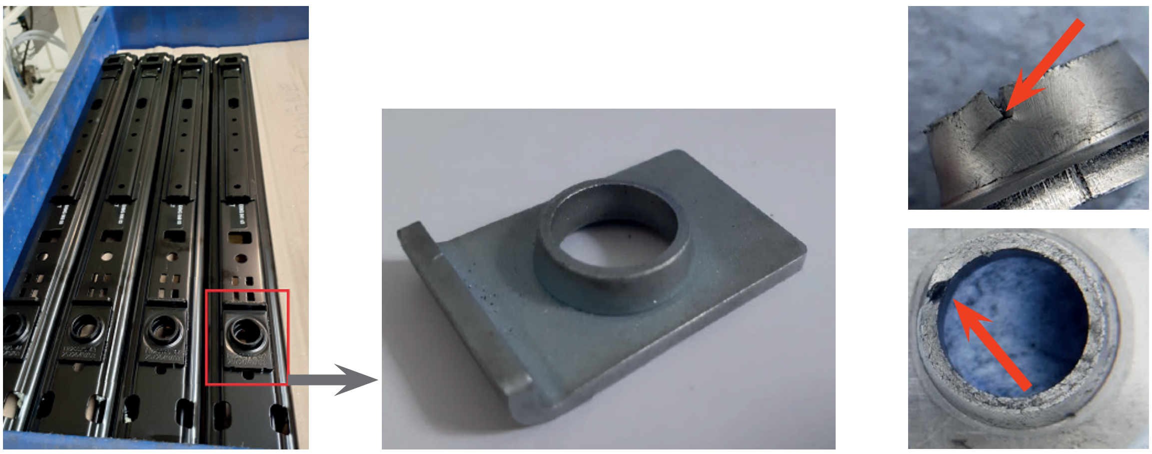


Fig. 1. Flanged component: a) as part of the car seat guide; b) separated workpiece; c) cracks on workpiece flange

a) b) c) d)

Fig. 2. Operations of hollow flange part process: a) laser cutting, reaming and machining the hole; b) bending of the side edge; c) flange forming; d) flange calibrating

Since the production process of the described part took place during the COVID-19 pandemic and global supply problems, the manufacturer was forced to change the supplier of steel sheet constituting the material of the product. For this purpose, the original HR-420LA material was replaced with S420MC, as it has a similar chemical composition and mechanical properties. Due to the above changes, the first problems with increased flange defects were initially attributed to the material. However, when it was possible to return to the original material recommended by the documentation, the defectiveness of the product did not decrease. As a result, the case was redirected to the R&D department in Faurecia which was asked to solve the problem.

A special research plan was developed, and the detailed results with crucial conclusions have been described in the diploma thesis of one of the authors of this paper, Wójcik (2022). The technological process was presented and analysed in this thesis, and it was established that the defect of cracks on the flange may result from the heat-affected zone created in the operation of laser cutting. This phenomenon is widely described in the literature (Julian & Gupta, 2020; Sheng & Joshi, 1995), and seems to have a significant impact on the described process. The considerations included in this work allowed to development of a set of process parameters, minimizing the defectiveness of the product and the data from the experiments were used for further statistical analysis based on various hypotheses.

2. Design of experiment and developing criteria for evaluating the results

As part of the experiment planning to investigate the causes of defects and determine the optimal process conditions, it was planned to consider five process parameters at different levels of variability:

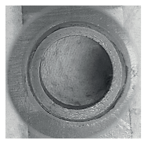
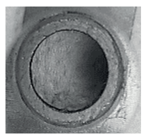
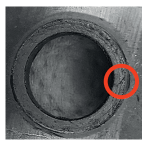
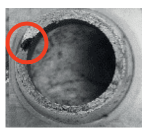
1. material (HR420LA, S420MC);
2. diameters of laser cut hole (3.0 mm, 5.0 mm, 5.6 mm);
3. diameters of reamed hole (3.9 mm, 5.9 mm);
4. hole machining after reaming (grinding, chamfering);
5. workpiece arrangement (top, bottom).

The workpiece arrangement implies the position of the detail in the flanging operation in relation to the side used in the laser cutting operation, where the top refers to the cutting operation and the bottom is opposite to the cutting operation.

Samples and variables were selected based on the engineering knowledge and production practice of the authors. The number of levels of variability of variables has been limited to the needs of a specific production problem (how to properly produce a part for another material). Five variables were selected as significant at two levels of variation (in addition to the diameter cut by laser), which gave 24 variants of variable selection. As a result of the above options, 24 test variants were adopted, and 25 samples were made for each variant which gave 600 cases for defect analysis. All cases were considered in the analyses.

As part of an initial analysis of the results, it was necessary to introduce a special classification to assess the defects. This was because the requirements of the customer ordering the product did not clearly reject the crack but determined its permissible size. In addition, according to the mechanism of plastic crack formation, the evaluation also considered the phenomenon of increased roughness which indicates the limit deformations have been exceeded. It was not critical in regard to product disqualification; however, it indicates warning strains in the process. The visible cracks lower than 0.5 mm has also been classified as non-critical. In view of the above, our own classification of the assessment of defects was introduced, and in order to consider its validity in the analyses, appropriate weights were assigned (Tab. 1).

Table 1. Classification of flange defects

Defect class	Visualization	Weight
No defects		0
Increased roughness of the flange face		1
Acceptable cracks		2
Unacceptable cracks		3

After all the experiments, each of them was assigned a weight corresponding to the defect from Table 1 and an analysis of the results was performed to investigate the defectiveness of the flanged part.

3. Evaluation of experimental results of defectiveness

First of all, a summary of all the results was made, and it was shown that among the tested samples, 65% were normal, and only in 12% a critical defect occurred, see Figure 3. The acceptable class of the defect (increased roughness and slight crack) was less than 1/4 of the samples.

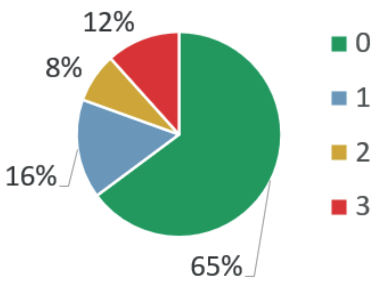


Fig. 3. Flange defect results in relation to defect class

Then, a comparison of the number of cases assigned to the defect class was made. To do so, the pivot plots were made with a distinction between all parameters divided into both tested materials (Fig. 4). The first observation is that samples from S420MC steel (orange bars in Figure 4) show a predominant defect in relation to HR420LA steel (blue bars in Figure 4). Although both materials have a similar chemical composition, S420MC has a lower uniform elongation, which may affect more frequent flange cracking due to the limit of circumferential strains being exceeded.

The second direct observation from the diagram in Figure 4 is noticeably greater defect of the flange formed from the 3 mm laser hole and reamed with a 3.9 mm drill. In this case, the drill removed the 0.45 mm layer, which for the laser-cut hole may have been too small, especially for the S420MC material. It is worth noting that the same geometric variant for the HR420LA material shows a much lower defectiveness.

The conclusions described above are only part of the complete analysis carried out by Wójcik (2022). However, it is worth remembering that the overriding goal was to obtain a set of parameters that meet the technological production requirements in order to minimize the likelihood of a defective product. Thanks to the analysis and juxtaposition with the one presented in Figure 4 it was possible to select two variants of process parameters, where defects occur the least for both options of the material used. The first of them (marked with black continuous rectangles in Figure 4) concerns the option closest to the documentation (laser diameter = 5.6 mm, reamed diameter = 5.9 mm) and informs that the hole after reaming should rather be chamfered and the plate should be laid in the upper position in relation to the cutting operation for further processing. The second case (marked with dotted line rectangles in Figure 4) indicates that it is best to cut a hole with a laser for a 5 mm diameter, to ream a diameter of 5.9 mm, and then to chamfer the hole edges. In this case, the arrangement of the piece is not of such great importance, and for both cases, the defect frequency is very low.

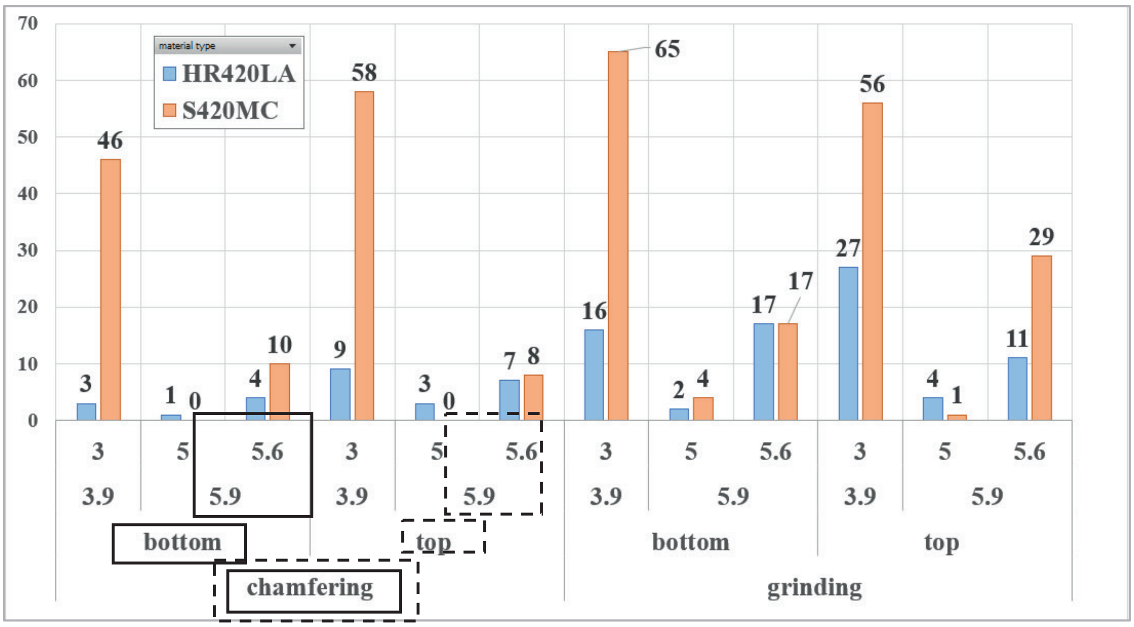


Fig. 4. Full diagram of defectiveness occurring in experimental cases

4. Process parameters on flange defectiveness impact

Although the main engineering goals have been achieved, and thanks to the obtained experimental results it was possible to minimize the chance of a defect using a comprehensive experiment plan, it was also possible to analyse the impact of individual input variables on the defectiveness of flange. While the analyses concern only one geometric shape of the product, the knowledge that could be gained during these considerations might also be useful for other geometric cases in processes using related machining operations. For this purpose, the methodology of statistical hypotheses was used, and the influence of the material, the reamed layer and the machining of the hole before shaping the flange were examined.

A two-sample location test of the null hypothesis, such that the means of two populations are equal, has been used in the statistical analysis. The variances of the two populations are assumed to be unequal. This test (also known as Welch's *t*-test) is referred to as independent samples *t*-tests, as it is typically applied when the statistical units underlying the two samples being compared are non-overlapping. Welch's *t*-test defines the statistic *t* by the following formula (1):

$$t = \frac{\bar{y}_1 - \bar{y}_2}{\sqrt{\dfrac{S_1^{\,2} - S_2^{\,2}}{n-1}}} \qquad (1)$$

where $\bar{y}_1$ and $\bar{y}_2$ are the sample mean and S_1 and S_2 are the sample standard deviation, and n is both samples size. The test statistic t was calculated and compared to critical value t_{cr} with degrees of freedom $f = n - 1$ and the significance level $\alpha = 0.05$. When $|t| < t_{cr}$ so the samples means are not significantly different.

The first zero hypothesis was that the type of sheet metal does not affect the occurrence of a defect in the process. As an alternative hypothesis, it was assumed nevertheless that the influence of the sheet metal exists. The significance level $\alpha = 0.05$ was considered. According to the procedure, the statistic test t was calculated and then compared with the critical value t_{cr}.

In the considerations, three options were studied for different cases of holes (laser diameter – reamed diameter) and full calculations are presented in Figure 5. According to the values of the calculated statistics for the case $d_{laser} = 5.0$ mm and $d_{reamed} = 5.9$ mm there is no reason for rejecting the H_o hypothesis what confirms that the material for this case is irrelevant (Fig. 5a). It is worth noting that the analysis of an analogous case for a smaller diameter ($d_{laser} = 3.0$ mm, $d_{reamed} = 3.9$ mm) indicates the need to reject of the H_o hypothesis due to the obtaining of the t statistic result of a slightly higher t_{cr} value (see Figure 5b), what indicates the significance of the material impact. However, for the case of a small, reamed layer ($d_{laser} = 5.6$ mm, $d_{reamed} = 5.9$ mm), the influence of the material seems to be even greater, as indicated by the obtained value of the statistic $t = 12.696$ significantly exceeding the statistic t_{cr}.

Another variable analyzed in terms of its impact on the occurrence of defects was the location of the workpiece (top or bottom). This analysis was carried out considering two cases: the first for the option with a large, reamed layer ($d_{laser} = 3$ mm and 5 mm) and for a small, reamed layer, i.e. for $d_{laser} = 5.6$ mm). In this analysis, it was also assumed that the H_o hypothesis means that the parameter does not affect the defect, while the alternative hypothesis indicates that the effect exists. From the pivot chart gathering all cases shown in Figure 6a, it is difficult to clearly indicate whether an effect of the workpiece side exists, but the calculation of statistics indicates that at laser diameters of 3 mm and 5 mm some influence exists. However, for a laser diameter 5.6 mm there is no basis for rejecting the H_o hypothesis, which means it can be accepted, and thus the side of the position of the sample for this case is not significant.

a)

y1	0.100
y2	0. 050
n	100
f	99
α	0.05
S1	0.770
S2	1.095
t	0.373
t_{cr}	1.984

b)

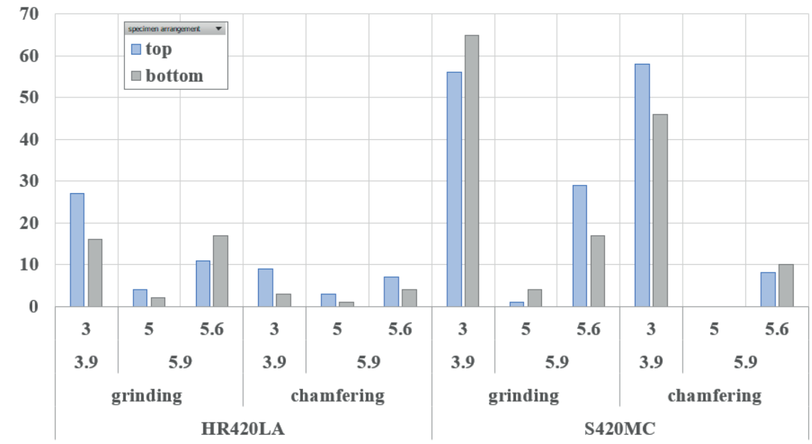
y1	0.390
y2	0.640
n	100
f	99
α	0.05
S1	0.680
S2	0.8350
t	2.321
t_{cr}	1.984

c)

y1	0.550
y2	2.250
n	100
f	99
α	0.05
S1	0.770
S2	1.095
t	12.696
t_{cr}	1.984

Fig. 5. Results of calculations for hypotheses checking the influence of material on the occurrence of defects for different hole geometric variants: a) laser diameter = 5.0 mm, reamed diameter = 5.9 mm; b) laser diameter = 3.0 mm, reamed diameter = 3.9 mm; c) laser diameter = 5.6 mm, reamed diameter = 5.9 mm

a)



b)

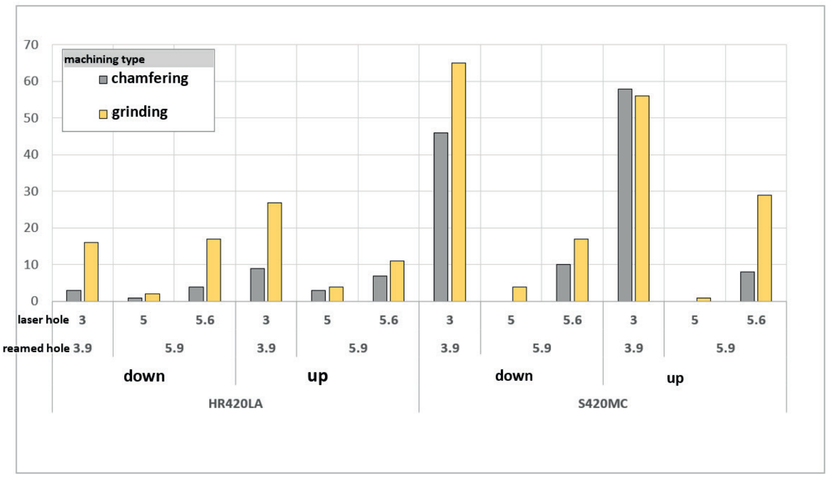
y1	0.600
y2	0.875
n	300
f	299
α	0.05
S1	1.143
S2	1.133
t	2.958
t_{cr}	1.984

c)

y1	0.480
y2	0.550
n	100
f	99
α	0.05
S1	1.143
S2	0.796
t	0.502
t_{cr}	1.984

Fig. 6. Investigation of the influence of the position of the workpiece on the occurrence of defects: a) pivot chart for all cases; b) statistical calculations for laser diameter of 3.0 mm and 5.0 mm; c) statistical calculations for laser diameter of 5.6 mm

a)



b)

y1	0.340
y2	0.150
n	100
f	99
α	0.05
S1	0.589
S2	0.575
t	2.958
t_{cr}	1.984

c)

y1	0.740
y2	0.290
n	75
f	74
α	0.05
S1	0.799
S2	0.671
t	3.734
t_{cr}	1.984

Fig. 7. Investigation of the hole machining type influence on the occurrence of defects: a) pivot chart for all cases; b) statistical calculations for HR420LA material; c) statistical calculations for d_{laser} = 5.6 mm, d_{reamed} = 5.9 mm

The last detailed analysis concerning the type of hole machining impact on the sample defect. For this purpose, two cases were selected, i.e., regarding the original production documentation, first for HR420LA material and the second for d_{laser} = 5.6 mm, d_{reamed} = 5.9 mm.

From the pivot chart for all cases regarding both types of machining (Fig. 7a), it is quite easy to see that for chamfering, there are much fewer defective cases than for grinding, which indicates that the influence of this parameter on defects exists. This was confirmed during hypothesis testing, both in terms of checking for defects in relation to the machining distribution for HR420LA (calculations in Figure 7b) and for the hole case d_{laser} = 5.6 mm, d_{reamed} = 5.9 mm (calculations in Figure 7c). In both cases, the t statistics exceeded the value of the critical statistics which allowed us to reject H_o hypothesis of no impact and thus to accept the alternative hypothesis that the effect of hole machining for both cases turned out to be significant.

5. Summary and conclusions

This paper presented the occurrence of defects in the flanges of automotive industry component. In order to carry out the engineering task of finding parameters that minimize the defectiveness of the product, a complex research plan was proposed. Based on the results obtained in experimental tests consistent with the accepted one, the following conclusions can be assumed:

– The research plan for the defect assessment made it possible to achieve an engineering result and to determine the optimal process parameters necessary to minimize defects in the process.
– The study of individual process parameters using statistical hypotheses has extended the knowledge of their significance for defectiveness under specific process conditions.

The obtained effects may be the basis for further work enabling the optimal selection of process parameters for other process cases. This could be implemented, for example, by developing a rule model or decision trees.

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