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RESEARCH

# Load Capacity Comparison of Different Wet Multi-Plate Clutches with Sinter Friction Lining with Regard to Spontaneous Damage Behavior

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## ABSTRACT

*Wet multi-plate clutches are safety-critical components of drive trains. Failure and damage must therefore be strongly avoided. In contrast to long-term damage, spontaneous damage and failures are difficult to predict. Different authors have already theorized the influence of different parameters on the carrying capacity. This paper extends the analysis of these effects by conducting experimental investigations. Furthermore, an evaluation method that allows to compare different clutch systems regarding their load carrying capacity is presented. Clutch systems with variation of oil flow, plate thickness, coating and groove pattern were tested, and their results analyzed. Statistical methods were used to consider the variance of the measurements. Lastly, recommendations are formulated for the development of clutch systems concerning the load carrying capacity. Strong trends can be seen for the influences of the thickness of the steel plate and oil flow rate, but these can only be statistically substantiated for the variation of the oil flow rate. For the variation of the coating and the grooving, only slight to no differences are discernible.*

## 1. INTRODUCTION

Wet-running (oil-cooled) multi-plate clutches and brakes are applied in many areas of drive technology. They are used for frictionally engaged torque transmission. In addition to brakes for decelerating vehicles, clutches enable the shifting of drivelines under differential speed. Multi-plate clutches and brakes are also used to protect a drive train from overload. In addition to the numerous industrial applications, e.g. as slipping clutches or as engagement clutches, clutches are widely used in the automotive industry (differential locks, shift clutches). Multi-plate clutches and brakes are usually safety-relevant components. They are subjected to high thermal and mechanical stresses [1].

This article deals with the spontaneous damage behavior of wet-running multi-plate clutches with sinter friction lining. With the use of a comparative method, the load carrying capacity of different clutch systems with regard to spontaneous damage is to be compared on the basis of experimental data. The relationship between sliding time and friction work is modeled through Linear Regression. Confidence bands are calculated to account for measurement uncertainties and variance and to allow comparison. Design recommendations will be derived on this data.

## 2. SPONTANEOUS DAMAGE BEHAVIOR OF CLUTCHES

The damage mechanisms of multi-plate clutches can be subdivided into spontaneous and long-term damage, depending on the time of occurrence. Long-term damage leads to wear or a continuous change in the friction system over several, sometimes tens of thousands, of shifting operations. In contrast, spontaneous damage is caused by a few shifting operations under extreme mechanical and thermal stress. Spontaneous damage is particularly problematic because it can lead to clutch failure through a single engagement and thus cannot be detected in the preliminary stages [2].

In the literature, thermoelastic instabilities (TEI) are considered to be causal for the forming of hot spots on friction systems [3–7]. The mechanism of action of thermoelastic instability was first described by Barber [7]. Accordingly, unequal load distributions in the contact area lead to undue heat input and hence to local temperature increases in the friction area. This results in varying degrees of thermal expansion, which amplifies the initial local pressure unevenness. This increased pressure unevenness leads to further local thermal overload. At subordinate wear amounts, the system finally becomes instable, and hot spots begin to form. This is a self-amplifying effect and can lead to the destruction of the friction system within a few operations.

Duminy et al [8,9] investigated the damage behavior of wet-running multi-plate clutches with the friction combination of steel and sintered bronze. The damage patterns for spontaneous damage were wear, clogging of the sintered surface, clogging of the lining pores, cracking of the lubricant, light and heavy sinter transfer, and buckling of the steel plate. Buckling of the steel plates (inversion of more than 0.1 mm) was defined as a failure criterion. Pfleger [10–12] subdivides the spontaneous damage form sinter transfer into three classes. Sinter transfer is defined as an increase in the coefficient of friction due to the scuffing of the friction material and the steel plate. Light sinter transfer defines an increase in the coefficient of friction of up to 15%, while heavy sinter transfer is characterized by an increase in the coefficient of friction of at least 30%. Medium sinter transfer ranges between the two classes. In addition, the area affected by sinter transfer can be included in the evaluation. As a result of sinter transfer, which is caused by thermal overload, the pores of the lining plate are also clogged, thus confirming Duminy's [9] results. Schneider [13] first differentiates spontaneous damage between the damage patterns discoloration of the steel plate (VF) and sinter transfer (SÜ). He further subdivides these damage patterns into large-area and local damage. A friction coefficient increase of at least 20% is specified as a failure criterion.

Duminy et al. [8,9] define a performance limit for sintered metal friction clutches. The performance limit is thus described by the permissible spec. shifting work, which is higher the lower the spec. frictional power of the associated shifting. In addition, the shift frequency, i.e. the number of shifts per time unit, is taken into account. In later work, the relationship between spec. friction work and maximum spec. friction power at the onset of damage is confirmed [14–19].

Various suggestions have been made in the literature to increase the performance limit of wet-running multi-plate clutches with respect to hot spots. Zagrodzki [20] shows in simulation that thermoelastic stability can be achieved by reducing the steel plate thickness. However, it should be noted that this reduces the thermal capacity and increases the temperature level for the same applied load. Also, thinner steel plates tend to buckle more than thicker ones. In addition, Kumar et al. [21] propose to increase thermal effusivity and thermal conductivity of the friction plates. Wu [22] shows in simulations that an increased cooling oil flow rate increases the cooling capacity and thus results in lower friction surface temperatures, which can reduce the tendency to damage. After Barber [7] describes pressure unevenness as one of the causes of hot spots, Fieldhouse [23] suggests the use of friction materials with a low Young's modulus. As a result, thickness differences of the plates result in lower pressing unevenness. The influence of the Young's modulus on the formation of hot spots has been demonstrated several times in the literature [13,16,24–26].

The aim of this work is to investigate the load capacity of wet-running multi-plate clutches with sinter friction lining with regard to the spontaneous damage behavior and to propose design suggestions for higher load capacity. In the literature, usually only single design parameters for a specific load point are compared. Statistical scatter of experimental results is not considered. In this paper, experimental investigations are carried out on different coupling variants. The parameters steel plate thickness, oil flow rate, steel plate coating and groove are varied. Experiments are carried out for load shifting in a wide range of friction work and friction power. A statistical method is used to compare and evaluate these results. Finally, design recommendations are given for increasing the load-carrying capacity with regard to spontaneous damage.

## 3. TEST METHOD TO INVESTIGATE SPONTANEOUS DAMAGE BEHAVIOR OF WET MULTI-PLATE CLUTCHES

The following sections present the Design of Experiment (3.1) and the evaluation methods. Sections 3.2 explains the basics and prerequisites of Liner Regression. Section 3.3 introduces the calculation of confidence bands.

### 3.1 Design of experiment

The series of experiments are carried out as step tests, which rely on the principle of the stepwise increase of the load as the test progresses. Hensel [27] and Strebel [28] have previously demonstrated the validity of this test methodology.

Before the tests are carried out, the parts must pass through the running-in process so that possible inaccuracies from manufacturing can be eliminated. The loads of the run-in are listed in Table 1.

**Table 1.** Load during run-in.

| Engagements | Pressure in N/mm² | Spec. friction work in J/mm² |
|---|---|---|
| 1000 | 0.5 | 0.5 |

Each clutch system is subjected to different test groups. Between the different groups, the pressure and the moment of inertia were varied. One group consists of 10 load levels, which differ in their initial differential speed.

To ensure that the results of the analysis are also statistically significant, 10 engagements are performed per load level. This number of engagements is also small enough to assure that the clutch systems do not experience long-term damage [28]. Based on Strebel's [28] observations, a cycle time of 40 seconds was chosen, which is long enough to ensure cooling of the clutch after each engagement.

Changes and damages to the plates are documented after each engagement. The load level is increased until sintered transfer with friction coefficient increase by more than 20 % can be observed, which is classified as failure of the plate. The definition of the failure criterion is taken from Strebel [28]. The initial damage consists of the discoloration of the steel plate. Figure 1 shows the mentioned damages. The complete experimental design is compiled in Appendix A. A more detailed description of the experimental procedure can be found at Schneider [29].

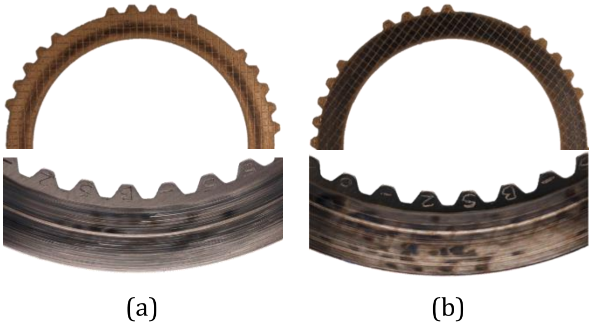

(a) (b)

**Fig. 1.** (a) Photos of the initial damage of the plates; (b) Photos after the failure criterion has been reached.

### 3.2 Linear regression

Linear regression forms a relationship between input variables and output variables [30]. The performed experiments produce a pair of values for friction work and sliding time for each test. In order to model the overall relationship, a regression line is constructed that best represents these data points. In cases with one input variable and one output variable the relationship is given by the following equation:

$$y = \beta_0 + \beta_1 \cdot x + e \tag{1}$$

where $\beta_0$ is the intercept, $\beta_1$ the slope of the regression line and $e$ the error term.

The optimal parameters $\beta_0$ and $\beta_1$ that best fit the given data points can be calculated based on the least sum of squares of the residuals (RSS) and are obtained by minimizing the following expression:

$$\mathrm{RSS}(\beta_0, \beta_1) = \sum_{i=1}^{n} (y_i - (\beta_0 + \beta_1 \cdot x_i))^2 \tag{2}$$

As stated by Ehle [31], a series of assumptions must be checked to allow a valid analysis of the regression lines further on:

a) Linearity: the relationship between the independent and the dependent variable must be linear.

b) The expected value of the residuals is zero ($E(e) = 0$).

c) Homoscedasticity: the residuals have constant variance.

d) Independence of error: the residuals do not correlate with each other.

e) Residuals are normally distributed.

These assumptions are further verified in Section 5. The methods used to verify these assumptions were explained in Strebel [28], Dreger [32], and Lilliefors [33].

### 3.3 Confidence band

According to Ehle [31], the confidence band of the mean value forms an interval for the expected value for the output variable for a given input with a given uncertainty α. The formation of the confidence band allows a better comparison of two or more regression lines regarding significant statistical differences. As there are uncertainties and inaccuracies during the measurement due to the measurement as well as due to the natural variance between the experiments, the regression line also inludes respective residual errors. Different variants can only be poorly compared without considering the overall quality and uncertainty of the regression lines. By considering the confidence bands, these uncertainties are quantified and are thus included in the comparison. Figure 2 shows the confidence band for the expected value of the output for the given data points.

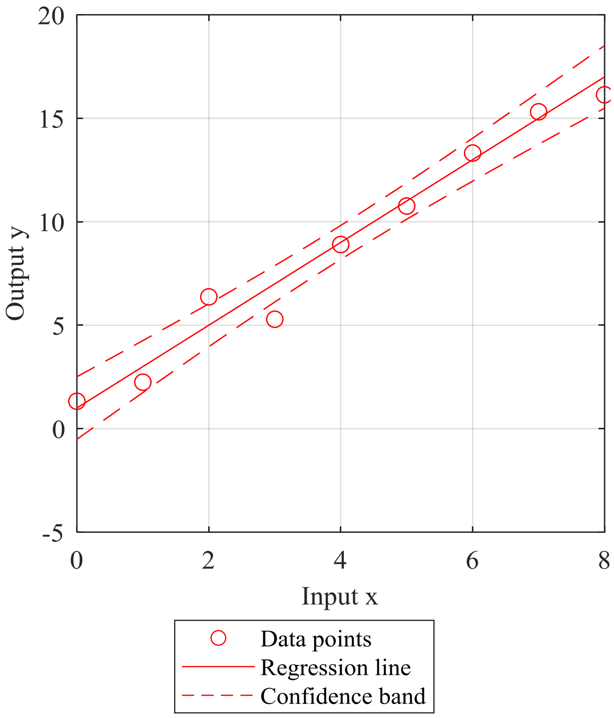


**Fig. 2.** Confidence band for a regression line.

The confidence interval is given by Ehle [31]:

$$CI = [I_1; I_2] \tag{3}$$

with

$$I_1 = \hat{y}(x) - t_{1-\alpha/_2, n-2} \cdot SE(\hat{y}(x)) \tag{4}$$

$$I_2 = \hat{y}(x) + t_{1-\alpha/_2, n-2} \cdot SE(\hat{y}(x)) \tag{5}$$

and the standard error for the expected value

$$SE(\hat{y}(x)) = s_{res} \sqrt{\frac{1}{n} + \frac{(x - \bar{x})^2}{{s_x}^2 (n-1)}} \tag{6}$$

in which $t_{1-\alpha/_2, n-2}$ is the student-t distribution with the significance level $\alpha$ and $n - 2$ degrees of freedom; $\hat{y}(x)$ is the expected value for an input $x$; $s_x$ is the standard deviation for the input $x$; and $n$ is the number of measurements. This evaluation method has already been successfully used by Schneider for investigations of paper friction linings [29].

## 4. TEST RIG, TEST PARTS

### 4.1 Component Test Rig ZF/FZG KLP-260

All tests were performed on a ZF/FZG KLP-260 component test bench. Further information about the test bench were described by Meingaßner [34].

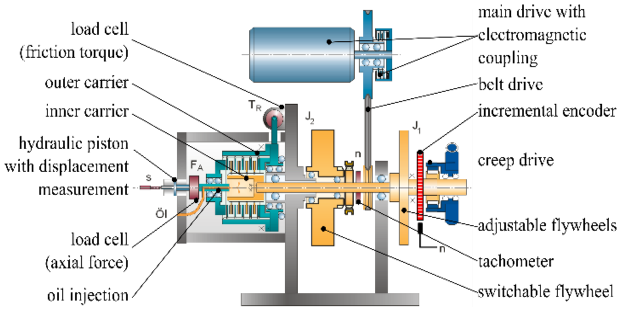


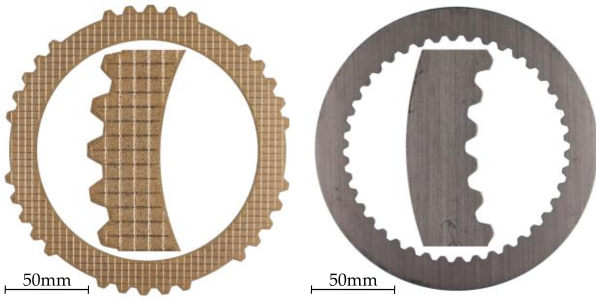
**Fig. 3.** Concept of Test Rig ZF/FZG KLP-260 [34].

### 4.2 Test parts

The clutch systems consist of an inner steel plate and an outer plate with sintered lining. Figure 4 shows photographs of one plate with sintered lining.

**Table 2.** Load during run-in.

| | |
|---|---|
| Outer diameter | 164 mm |
| Inner diameter | 132 mm |



(a) (b)

**Fig. 4.** (a) Friction plate; (b) steel plate.

The experiments are carried out on 5 different clutch systems, with one system serving as reference system. Table 3 lists the parameters for each clutch system. The modified parameter for each clutch system is underlined.

**Table 3.** Specification of the tested variants.

| Variant | Oil flow rate in $mm^3/mm^2s$ | Plate thickness in mm | groove | coating |
|---|---|---|---|---|
| Refer-ence | 0.8 | 1.5 | waffle  | - |
| A | 0.4 | 1.5 | waffle  | - |
| B | 0.8 | 3 | waffle  | - |
| C | 0.8 | 1.5 | waffle  | nitrided steel plates |
| D | 0.8 | 1.5 | sun-burst  | - |

## 5. RESULTS

For each variant and for the reference system the regression lines and 90% confidence bands for the expected value are formed. For the analysis, the load levels where local discoloration occurs and the level before failure are used. The failure level is not used due to the inaccuracy of the measurements during the failure. As input variable for the linear regression the sliding time $t_s$ is used and as output variable the spec. friction work $q_s$. The linearity of the relationship was demonstrated by Strebel [28]. The relationship is described by the following equation:

$$q_s = \gamma \cdot t_s + q_{s,0} \tag{7}$$

The results of the linear regression are presented in Table 4.

**Table 4.** Results of linear regression

| System | First damage | | Prior to failure | |
|---|---|---|---|---|
| | $\gamma$ | $q_{s,0}$ | $\gamma$ | $q_{s,0}$ |
| Reference | 0.3268 | 0.5436 | 0.4745 | 0.5644 |
| Variant A | 0.2212 | 0.6033 | 0.3954 | 0.6076 |
| Variant B | 0.4376 | 0.5310 | 0.4992 | 0.5667 |
| Variant C | 0.4027 | 0.4999 | 0.4524 | 0.5640 |
| Variant D | 0.3601 | 0.5287 | 0.3945 | 0.5587 |

Statistically significant statements can be made regarding differences in the load carrying capacity for those areas in which the confidence bands of the two regression lines do not overlap. If the confidence intervals overlap, no statements can be made in this sense. This does not mean that differences do not exist. These just cannot be explored with this method.

The next paragraphs present the results of the assessment of the assumptions and prerequisites of section 3.2.

Table 5 shows the expected value for the residuals of the regression lines. Both values are smaller than $10^{-10}$ and therefore the assumption that the expected value for the residuals is zero can be justified.

**Table 5.** Expected value of the residuals.

| Load level | E[e] |
|---|---|
| First damage | $1.78 \cdot 10^{-17}$ |
| Prior to failure | $4.44 \cdot 10^{-17}$ |

Figure 5 shows the dependence of residuals on spec. friction work for all calculated regression lines. The data shows no visible trend or pattern. Therefore, the variance can be assumed to be constant.

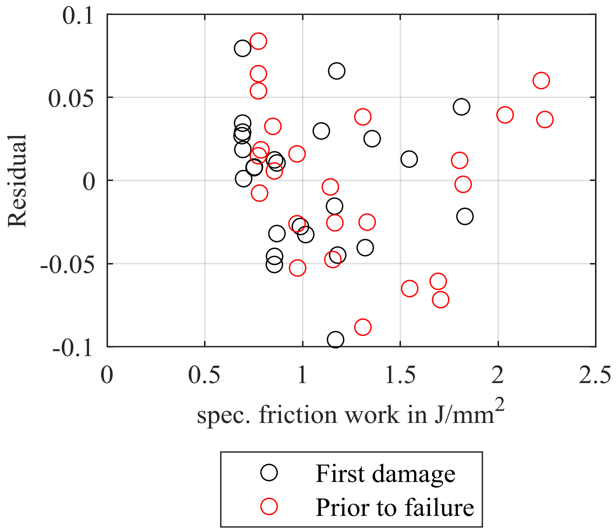


**Fig. 5.** spec. Friction work $q_s$ vs residuals $e_i$.

The residuals of the regression lines are normalized, and the Kolmogorov-Smirnov test is performed to examine the normality of the residuals. The results of the Kolmogorov-Smirnov test are presented in Table 6. Since the test-value $D$ is smaller than the critical value $D_{crit}$ for $n = 24$ and $\alpha = 0.05$, it is possible to assume that the residuals follow a standard distribution.

**Table 6.** Results of Kolmogorov-Smirnov test

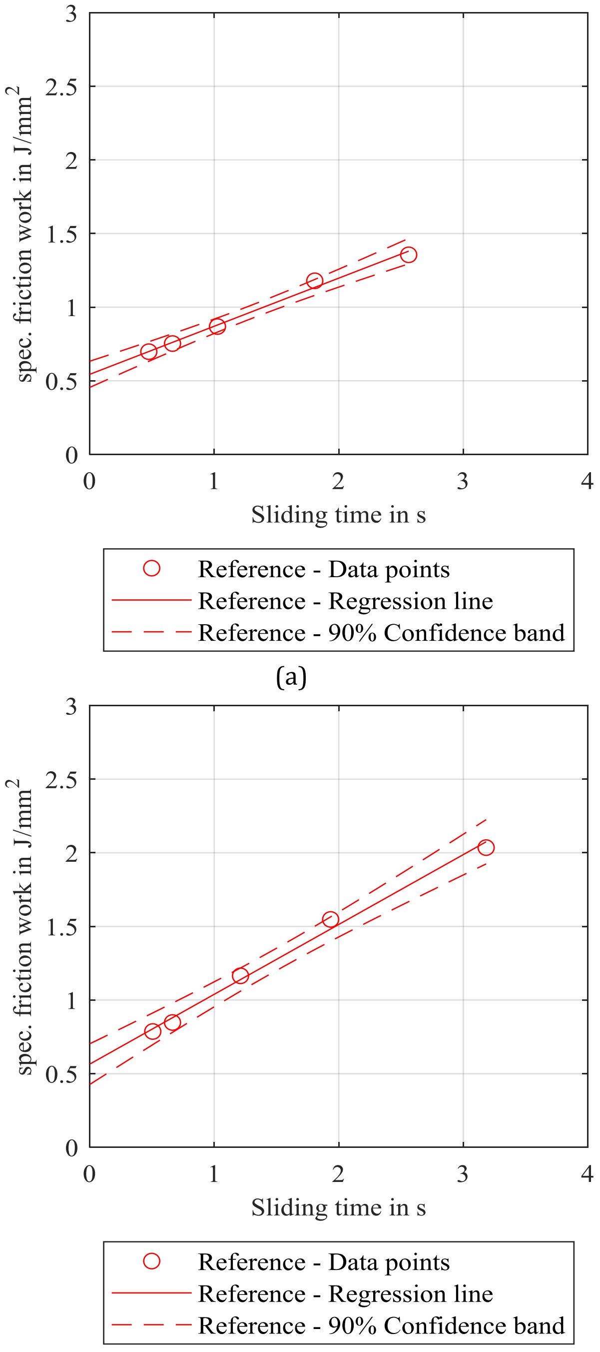
| Load level | $D$ | $D_{crit,0.05}$ |
|---|---|---|
| First damage | 0.136 | 0.269 |
| Prior to failure | 0.087 | 0.269 |

The Durbin-Watson test is used to assess first-order autocorrelation. The test statistics for the initial damage is $DW = 2.05$ and $DW = 2.06$ for the level prior to failure. For both cases the hypothesis of first-order autocorrelation can be rejected.

In the following sections the results for the variants A (lower oil flow), B (plate thickness), C (nitrided plate) and D (sunburst) are presented.

### 5.1 Reference group

Figure 6 shows the measurements, regression line and confidence bands for the first damage and load level prior to the failure for the reference system. The confidence band is calculated for a significance level of $\alpha = 0.1$.



(a)

(b)

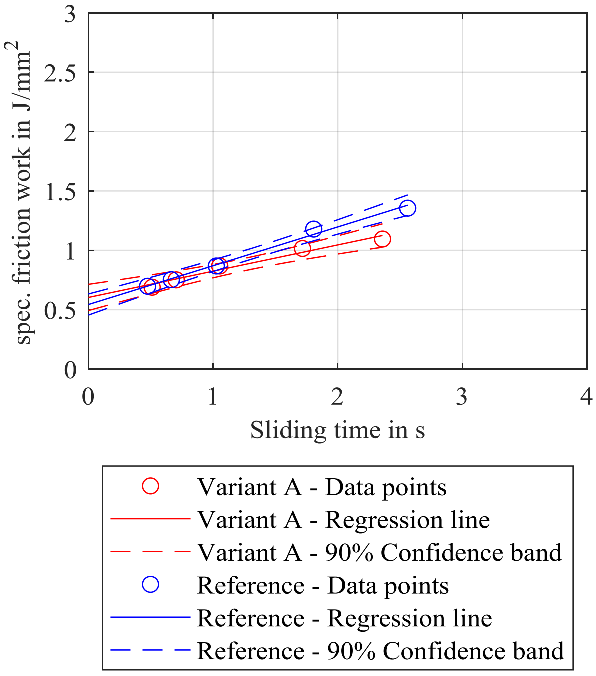
**Fig. 6.** (a) First damage – local discoloration; (b) load level prior to failure.

## 5.2 Variant A – oil flow rate

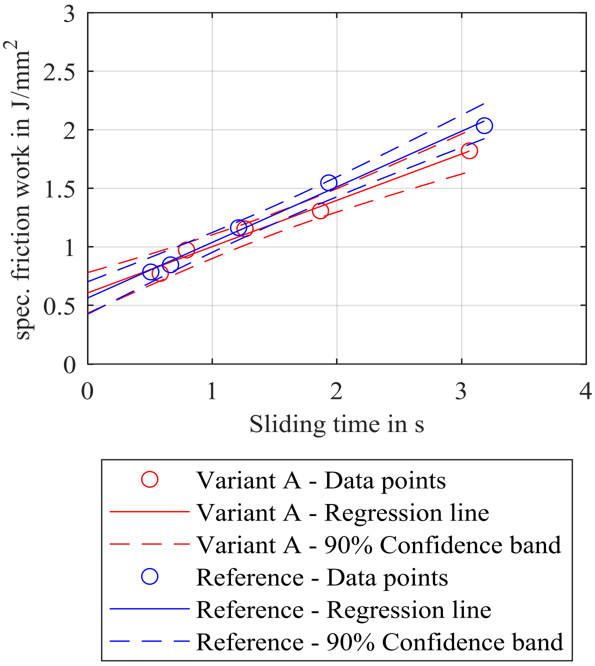
Figure 7 shows the comparison of variant A to the reference system regarding load carrying capacity. A lower oil flow of 0.4 mm³/mm²s instead of 0.8 mm³/mm²s was set for the tests of variant A.

The regression line of variant A is flatter than the regression line for the variance in the case of initial damage (Figure 7 (a)). Variant A has a slightly larger axis intercept $q_{s,0}$ and a smaller slope. The measurements for small sliding times have very similar values and the variant and the reference are hardly distinguishable. This changes for long sliding times. The higher the sliding time, the more the measuring points diverge. After a sliding time of about 1.7 seconds, the confidence bands of the two regression lines no longer overlap. Since there is no longer any overlap of the confidence bands, it is possible to state that the load capacity of variant A is significantly lower compared to the reference for the initial damage.

In the case prior to failure (Figure 7 (b)), the regression lines behave similar to the initial damage. The measurements for both clutch systems are close together for small sliding times and diverge for larger sliding times. However, no statistically significant statements can be made since the confidence bands still overlap.



(a)



(b)

**Fig. 7.** (a) First damage – local discoloration; (b) load level prior to failure.

## 5.3 Variant B – plate thickness

The comparison of the load carrying capacity for the reference and variant B is shown in Figure 8. Both variants were subjected to the same test conditions. Variant B has an increased plate thickness (3 mm instead of 1.5 mm). This was solved by using two steel plates with 1.5 mm.

In the case of initial damage, the regression line for the thicker variant is considerably steeper than the regression line for the reference. The axis intercept for both systems is nearly the same. The differences between the regression lines for the initial damage are clearly visible. However, the measurements of variant B have a greater variance around the calculated regression line. The higher variance compared to the reference results in a wider confidence band. From 0 to 1.5 seconds both confidence bands overlap. After 1.5 seconds the confidence bands of the two variants touch but do not overlap. Therefore, it is not possible to make statements about significant differences using this method. Nevertheless, a trend is recognizable for the variant with thicker plates.

This trend is not visible for the case prior to failure. Both regression lines behave very similar. The axis intercept $q_{s,0}$ for variant B and for the reference are the same. The slope $\gamma$ of both regression lines differ by only 5%.

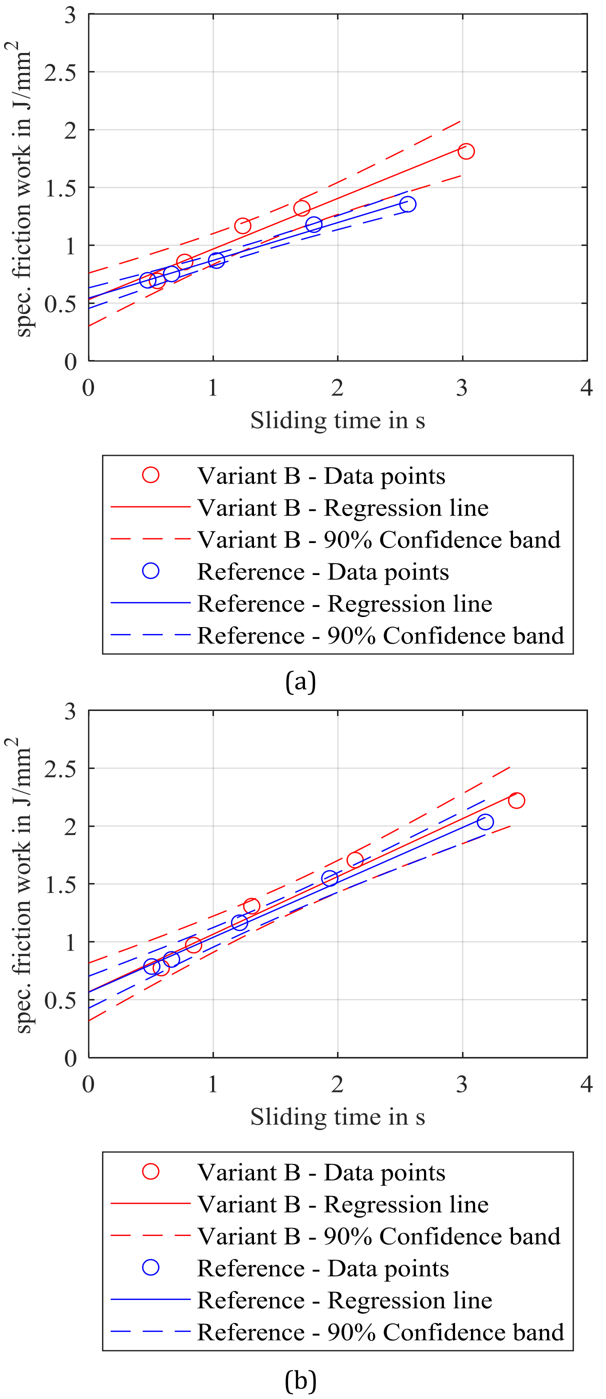


**Fig. 8.** (a) First damage – local discoloration; (b) load level prior to failure.

## 5.4 Variant C – nitrided steel plates

Variant C consists of a clutch system with nitrided plates. Figure 9 shows the measurements, regression line and 90% confidence band for the variant C and the reference.

The variant with nitrided steel plates shows no visible differences in both plots. Small trends can be seen, especially in the case of initial damage (Figure 9 (a)). The regression line for variant C is steeper than the line for the reference and both have a similar intercept value $q_{s,0}$. Since the confidence bands still overlap, no significant statements of any kind can be made. In the case prior to failure (Figure 9 (b)), both regression lines have almost exactly the same course. The slopes differ by less than 5% and the axis intercepts by less than 1%. Therefore, no statement can be made as to whether nitrided plates influence the load capacity of the clutch system.

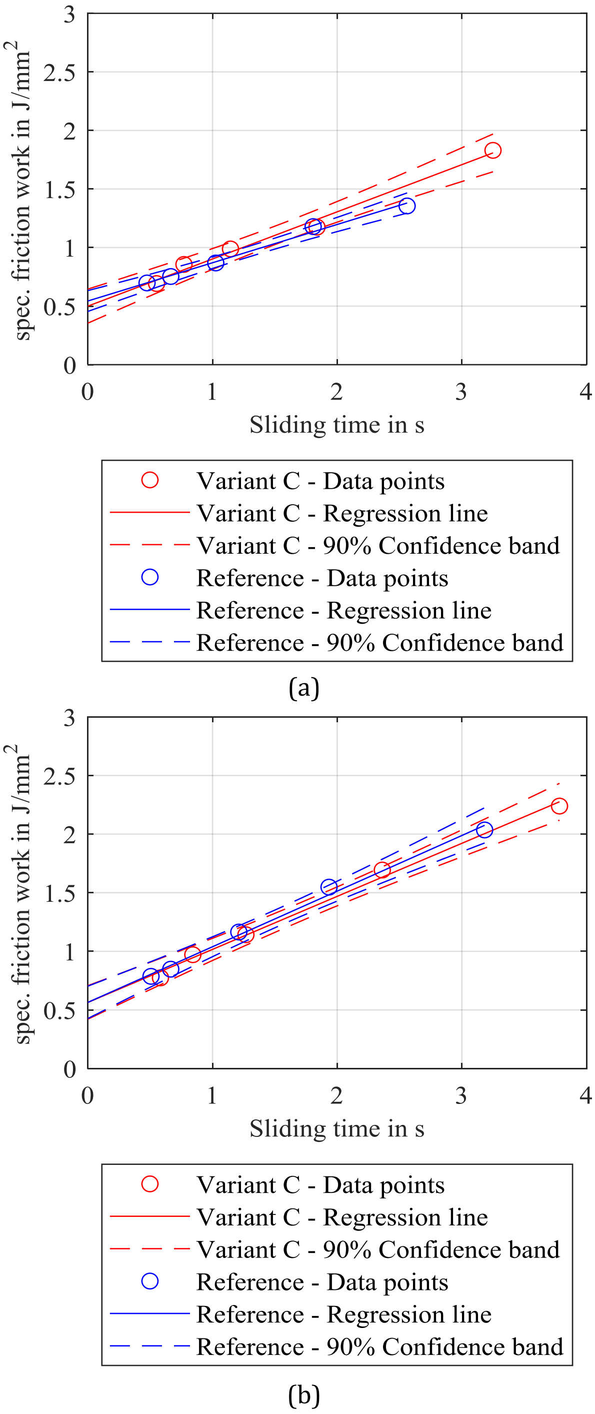
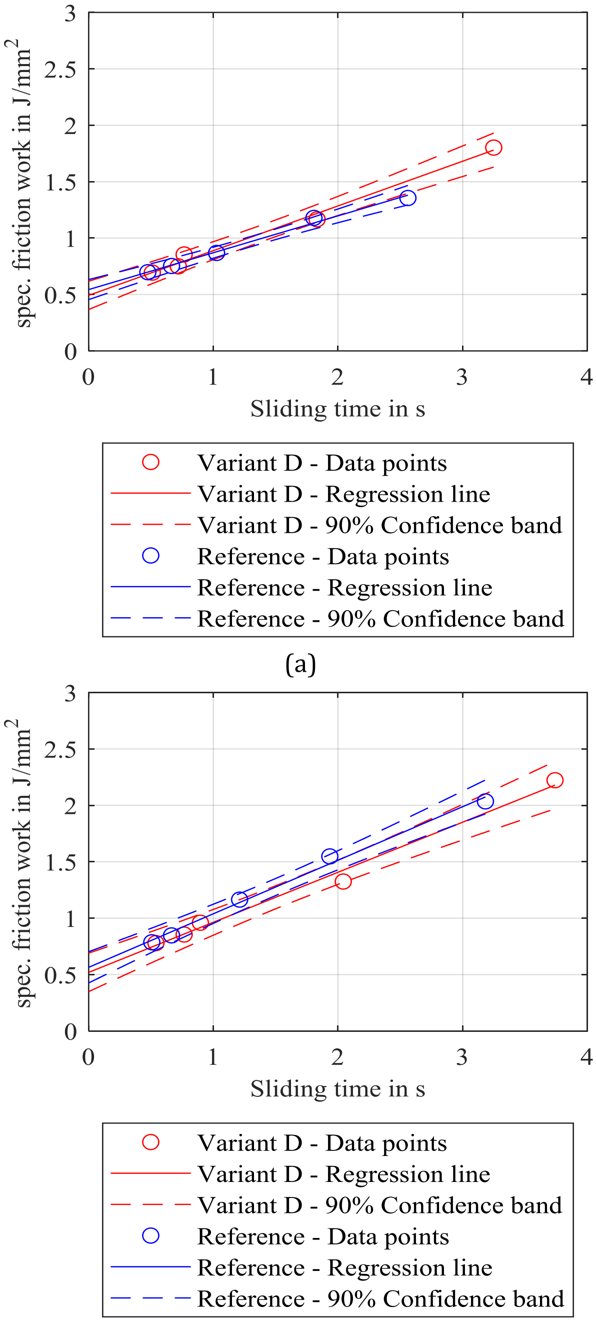


**Fig. 9.** (a) First damage – local discoloration; (b) load level prior to failure.

### 5.5 Variant D – sunburst grooves

Figure 10 shows the comparison of variant D to the reference system regarding load carrying capacity. In the case of initial damage (Figure 10 (a)), it is possible to detect a trend. Both regression lines have similar axis intercepts. Yet the regression line for variant with sunburst grooves is steeper than the regression line for the reference. This trend is too weak to allow any formulation of a significant statement. The confidence intervals of the two regression lines overlap for all sliding times.



(a)

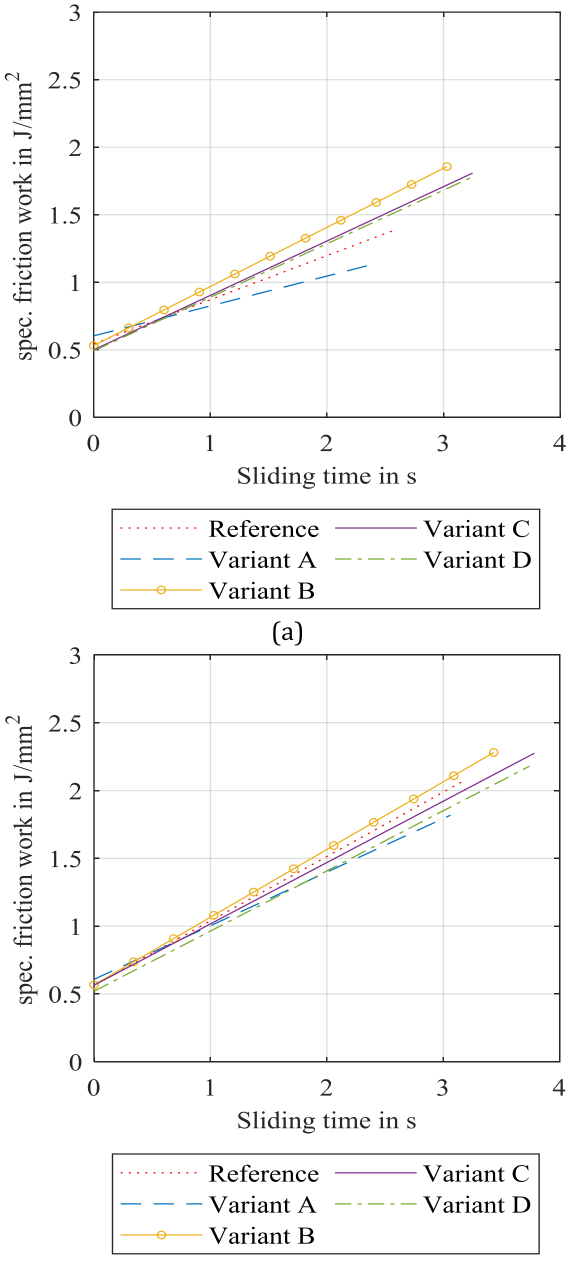
(b)

**Fig. 10.** (a) First damage – local discoloration; (b) load level prior to failure.

In the case prior to failure (Figure 10 (b)), both regression lines also behave similar. The slopes of the regression lines differ by less than 7%. The intercept value for variant D is slightly smaller than the value for the reference. The difference between the regression lines is too small to allow any statistically significant statement according to the presented method.

### 5.6 Comparison of variants

Figure 11 shows all the regression lines generated for the reference system and the four analyzed variants.



(a)

(b)

**Fig. 11.** (a) First damage – local discoloration; (b) load level prior to failure.

In the case of the initial damage (Figure 11a), it is evident that the reduction of the oil flow rate results in a significant reduction of the load-bearing capacity compared to the other variants. Both the use of nitrided steel plates and that of plates with sunburst grooves resulted in a weak, but very similar increase in load capacity. In the case of the clutches with thicker steel plates, the highest load capacity was obtained. With regard to the load level prior to failure, no major differences are discernible between the individual variants.

## 6. DISCUSSION

Based on the reference system, it is possible to observe that after the initial damage, there is a slight increase in the failure loads for long slipping times. The period in which the clutch is already damaged, but does not fail, is significantly larger for long sliding times than for short slipping times. For the latter case, the range between initial damage and failure is very small. This behavior is also observed for all other variants and confirms Strebel's [28] results.

The reduction of the oil volume flow leads to a flattening of the limit line for the damage of the clutch systems. In the case of long sliding times, there is a reduction in the load carrying capacity with respect to spontaneous damage. For initial damage, these observations are statistically validated. In terms of failure, the statement is not statistically significant, but a trend is recognizable. These experimental results can be reconciled with the simulative results of Wu [22], who simulates a lower friction surface temperature at higher oil flow rates.

As explained in section 2, according to Zagrodzki [21], the thermal capacity can be increased by increasing the steel plate thickness. This results in a reduction of temperature level for the same applied load. In the experiments, doubling the plate thickness does lead to a significant increase in load capacity at initial damage with longer slip times, but this is not statistically significant due to the increased variance of the measured values. Nevertheless, the trend is clearly discernible. No differences are discernible regarding the failure level.

Both the coating (variant C) of the steel plates and the grooving (variant D) resulted in a small increase in the load limit for initial damage for long slipping times. The nitration of the steel plate has no effect on the failure level of the clutch. However, the change in grooving resulted in a slight reduction in the load limit for failure.

With respect to the increase in load capacity regarding initial damages to the clutch system, the oil flow rate and the thickness of the plate can be considered as being the most relevant parameters. For long sliding times, it can be identified from the experimental results that higher oil volume flow rates raise the load limits. The increase of the plate thickness confirms the theoretical considerations of Zagrodzki [21]. Doubling the thickness increases the range in which the clutch systems can operate without damage, especially in the context of longer sliding times.

This adopted evaluation method only allows statements if the confidence bands do not overlap. In the future, the evaluation method can be extended to allow statements in case of overlapping. This enables all possible situations to be considered. Furthermore, it is of particular interest to examine the interactions between different variants, e.g. whether certain combinations increase the load-bearing capacity or whether two variants compensate the effects each other.

## 7. SUMMARY AND CONCLUSION

In this publication the load capacities of different wet-running multi-plate clutch systems were investigated. For this purpose, the following parameters were varied and their influences were examined: oil flow rate, plate thickness, coating and groove pattern.

All clutch systems undergo a run-in before the tests to compensate for inaccuracies in manufacturing. The tests consist of a step test with 10 load levels in which the loads are increased after each step. The stages where local discoloration occurs (initial damage) and one stage before failure were used for further analysis.

The linear regression is performed for all clutch systems and the results are presented for some relevant variants. The linear regression makes explicit the linear relationship between sliding time and spec. friction work. For each regression line a 90% confidence band for the expected value is formed.

The measured values, regression line and confidence intervals are plotted for each variant together with the reference.

After the analysis, some tendencies can be observed. However, these cannot be statistically substantiated. The only significant differences in the load carrying capacity that can be determined are in the initial damage caused by the variation of the oil flow rate. The load capacity of the variant with lower oil flow rate is smaller than the reference for long sliding times. This outcome should be taken into account during the design of the clutch system. If an extended sliding time is expected during operation, then the selection of a high oil flow rate is recommended in order to increase the load carrying capacity. There is no variation for small sliding times. The variation of the thickness, coating and groove pattern of the plates did not produce statistically significant differences, but, especially for the initial damage, some tendencies are visible. Although no statistically significant conclusions can be drawn, an outlook for the design recommendations can be presented. Considering the trends of the results, it might be beneficial during the design of the system to increase the thickness of the steel plate, to adopt nitrided steel plates or plates with sunburst grooves to increase the load carrying capacity. These aspects need to be verified in detail in future investigations. In addition, load-bearing capacity increases with respect to spontaneous damage due to the combination of these individual parameters need to be investigated in more detail.

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## APPENDIX A

Loads of step test 1

| Step | Sliding Speed in m/s | Friction Work in J/mm$^2$ | Pressure in N/mm$^2$ | Friction power in W/ mm$^2$ |
|---|---|---|---|---|
| 1 | 12,60 | 0,27 | 1,20 | 1,51 |
| 2 | 14,70 | 0,36 | 1,20 | 1,76 |
| 3 | 16,80 | 0,48 | 1,20 | 2,02 |
| 4 | 18,90 | 0,60 | 1,20 | 2,27 |
| 5 | 20,62 | 0,72 | 1,20 | 2,47 |
| 6 | 22,09 | 0,82 | 1,20 | 2,65 |
| 7 | 23,57 | 0,94 | 1,20 | 2,83 |
| 8 | 24,89 | 1,04 | 1,20 | 2,99 |
| 9 | 26,37 | 1,17 | 1,20 | 3,16 |
| 10 | 27,93 | 1,31 | 1,20 | 3,35 |

Loads of step test 2

| Step | Sliding Speed in m/s | Friction Work in J/mm$^{22}$ | Pressure in N/mm$^2$ | Friction power in W/ mm$^2$ |
|---|---|---|---|---|
| 1 | 10,19 | 0,27 | 1,00 | 1,02 |
| 2 | 12,37 | 0,40 | 1,00 | 1,24 |
| 3 | 14,31 | 0,54 | 1,00 | 1,43 |
| 4 | 16,18 | 0,69 | 1,00 | 1,62 |
| 5 | 17,81 | 0,84 | 1,00 | 1,78 |
| 6 | 19,22 | 0,97 | 1,00 | 1,92 |
| 7 | 20,62 | 1,12 | 1,00 | 2,06 |
| 8 | 21,94 | 1,27 | 1,00 | 2,19 |
| 9 | 23,18 | 1,42 | 1,00 | 2,32 |
| 10 | 24,51 | 1,58 | 1,00 | 2,45 |

Loads of step test 3

| Step | Sliding Speed in m/s | Friction Work in J/mm$^2$ | Pressure in N/mm$^2$ | Friction power in W/ mm$^2$ |
|---|---|---|---|---|
| 1 | 13,93 | 0,23 | 1,50 | 2,09 |
| 2 | 17,43 | 0,36 | 1,50 | 2,61 |
| 3 | 20,54 | 0,50 | 1,50 | 3,08 |
| 4 | 22,02 | 0,57 | 1,50 | 3,30 |
| 5 | 23,49 | 0,65 | 1,50 | 3,52 |
| 6 | 24,97 | 0,73 | 1,50 | 3,75 |
| 7 | 26,53 | 0,83 | 1,50 | 3,98 |
| 8 | 28,01 | 0,92 | 1,50 | 4,20 |
| 9 | 29,48 | 1,02 | 1,50 | 4,42 |
| 10 | 30,96 | 1,13 | 1,50 | 4,64 |

Loads of step test 4

| Step | Sliding Speed in m/s | Friction Work in J/mm$^2$ | Pressure in N/mm$^2$ | Friction power in W/ mm$^2$ |
|---|---|---|---|---|
| 1 | 15,79 | 0,36 | 0,48 | 0,76 |
| 2 | 19,99 | 0,58 | 0,48 | 0,96 |
| 3 | 23,18 | 0,77 | 0,48 | 1,11 |
| 4 | 25,91 | 0,97 | 0,48 | 1,24 |
| 5 | 28,01 | 1,13 | 0,48 | 1,34 |
| 6 | 30,03 | 1,30 | 0,48 | 1,44 |
| 7 | 32,21 | 1,49 | 0,48 | 1,55 |
| 8 | 34,31 | 1,70 | 0,48 | 1,65 |
| 9 | 36,41 | 1,91 | 0,48 | 1,75 |
| 10 | 38,51 | 2,14 | 0,48 | 1,85 |

Loads of step test 5

| Step | Sliding Speed in m/s | Friction Work in J/mm$^2$ | Pressure in N/mm$^2$ | Friction power in W/ mm$^2$ |
|---|---|---|---|---|
| 1 | 13,23 | 0,46 | 0,47 | 0,62 |
| 2 | 17,58 | 0,82 | 0,47 | 0,83 |
| 3 | 19,99 | 1,05 | 0,47 | 0,94 |
| 4 | 22,33 | 1,32 | 0,47 | 1,05 |
| 5 | 24,19 | 1,54 | 0,47 | 1,14 |
| 6 | 26,06 | 1,79 | 0,47 | 1,22 |
| 7 | 27,54 | 2,00 | 0,47 | 1,29 |
| 8 | 29,10 | 2,23 | 0,47 | 1,37 |
| 9 | 30,81 | 2,50 | 0,47 | 1,45 |
| 10 | 32,44 | 2,78 | 0,47 | 1,52 |