Chinese Journal of Mechanical Engineering

ORIGINAL ARTICLE

Running-In Behavior of Wet Multi-plate Clutches: Introduction of a New Test Method for Investigation and Characterization

Katharina Voelkel* , Hermann Pflaum and Karsten Stahl

Abstract

Wet multi-plate clutches are relevant components of modern drivetrain applications, not only in terms of function but also safety and comfort. Especially at the beginning of their lifetime, distinct changes of the friction behavior may occur and make the actuation of the clutch challenging. This transcript describes the typical running-in behavior of wet multi-plate clutches and gives a general definition for running-in of clutches. Moreover, a new test method to systematically investigate the running-in behavior of clutches is introduced. This test method contains a test procedure to characterize the running-in behavior on different load levels. Furthermore, a multi-stage procedure to evaluate and characterize the running-in behavior of clutches with mathematical approaches and new characteristic values is given. The quality of the test method is demonstrated on the example of three different tribological systems from dual clutch transmissions (DCT) and automatic transmissions (AT) application using paper friction linings.

Keywords: Clutch, Running-in, Test method, Paper friction lining
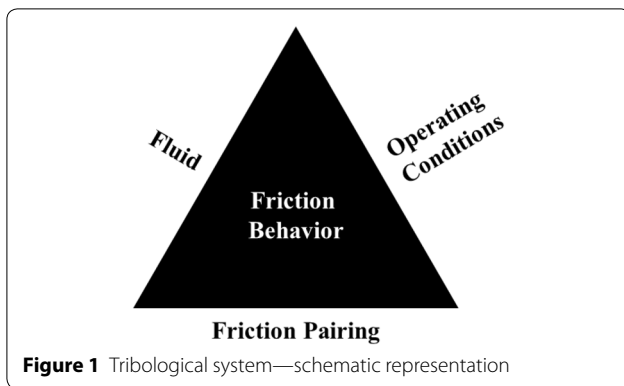
1 Introduction

Driving safety and comfort enhancements are highly relevant to development of modern drivetrain applications. As wet multi-plate clutches are important components of modern power shift transmissions, e.g., in automatic transmissions (AT), dual clutch transmissions (DCT) and limited slip differentials (LSD), the requirements for safety and comfort behavior of clutches are exacting. Functional behavior and shifting comfort of the clutch mainly depend on its friction behavior. Level and progression of the friction coefficient depend on the tribological system (see Figure 1) and therefore on fluid and operating conditions as well as types and conditions of steel and friction plates [1]. Both the base oil and its additives show a significant influence on the friction behavior of wet multi-plate clutches. Many detailed studies show effects of single additives and additive combinations on

the friction behavior in different tribological systems. Fundamental works are given by Ichihashi [2] and Mäki et al. [3], that are expanded regarding modern lubricants and friction materials by Ingram et al. [4] and Stockinger et al. [5]. Regarding the operating conditions, several works show an influence of sliding velocity, pressure and temperature on the friction behavior. Typically, the friction coefficient increases with sliding velocity (see Refs. [6, 7]). In addition, there is typically a decrease in friction coefficient with temperature (see Ref. [8]). The influence of the steel plate condition on the friction behavior is also an important research topic and is discussed in Refs. [7, 9, 10]. The influence of the steel plate is usually smaller than the influence of the friction pairing. Important parameters are porosity of the friction lining (see Refs. [11–13]) and proportion of the resin (see Ref. [14]).

2 Running-In of Wet Multi-plate Clutches

Especially at the beginning of use, when running-in processes are not completed yet, distinct changes in friction behavior may occur and lead to significant challenges in

---

*Correspondence: voelkel@fzg.mw.tum.de
Gear Research Centre (FZG), Technical University of Munich, Garching, Germany

Voelkel *et al. Chin. J. Mech. Eng.*   (2020) 33:34

Page 2 of 9

Figure 1 Tribological system—schematic representation

actuating the clutch. Therefore, it is important to be able to understand and characterize the running-in behavior of wet multi-plate clutches.

During running-in mechanical, chemical and physical changes of the component surfaces in contact take place. The result is an adaptation of the body in the contact area and a change in the tribological behavior.

Abbott and Firestone [15] described the running-in of technical surfaces in the year 1933: "When two newly machined surfaces are placed together, they touch only on the peaks of the highest irregularities, and the actual contact area is very small. If surfaces are 'running' under load, or otherwise fitted, the projecting irregularities are gradually removed and the actual area of contact is increased."

According to Blau [16, 17], frictional running-in is characterized by the overall trend in friction force with time, the duration of characteristic features in the curve of friction over time and the degree of frictional fluctuations as a superimposition of the general trend. Depending on the tribological system, changes in surface composition, microstructure, and third-body distribution may occur.

Running-in is often equalized with a decrease of friction (see Ref. [18]), since most of the research works on running-in behavior refer to a metal-metal-contact of rolling element surfaces. In addition, many works combine running-in with an increase in load-bearing liquid film by smoothing of the surfaces in contact (see Ref. [19]). These model representations are largely not transferable to clutches; moreover, the target of minimizing friction is not pursued for clutches.

The running-in behavior of wet multi-plate clutches is rarely in focus of research works, as most of these works focus on the friction behavior of the run-in clutch (see Refs. [20, 21]). If a running-in program is run, this serves to achieve a stable friction behavior. Wordings similar to the following are often found:

"After running-in, the friction coefficient was stable, and the test was then started" [22]. Conditions and duration of running-in programs as well as changes of friction behavior during running-in, are usually not discussed at all. Nevertheless, distinct changes to friction level and progression can occur during running-in of wet multi-plate clutches and can lead to clutch control challenges.

However, few research works describe respectively touch the topic of running-in behavior of wet multi-plate clutches.

Pokorny [23] provided the earliest description of the running-in behavior of wet multi-plate clutches in the year 1960. The level of the friction coefficient increased during running-in. He attributed this to larger contact areas in the friction contact of the run-in clutch compared to the new condition. Duminy [24] took up these considerations in the year 1979 and continued them: With an increasing number of shifting operations, the contact area in the friction contact increases and fluctuations in friction behavior decrease. Depending on the type of clutch, friction pairing and number of shiftings, a "quasi-stable" friction behavior evolves. Pfleger described in Refs. [25, 26], that, especially in the phase of running-in, the properties of the steel plate could influence the friction behavior of the clutch. Yesnik et al. described similar observations in their publication [27] on the friction behavior of steel plate variants with different surface surface treatments. As part of their work on the influence of the surface quality of the friction plate on the friction behavior, Zou et al. [28] briefly described the friction behavior during running-in. In the phase of running-in, different tests showed significant differences in friction behavior. The friction behavior stabilized with increasing test duration. Katsukawa [14] showed trends of friction coefficient for friction materials with different types of resins. Depending on the resin, there were differences, particularly in the running-in phase, both with regard to the development of the friction behavior and with regard to the level of the friction coefficient.
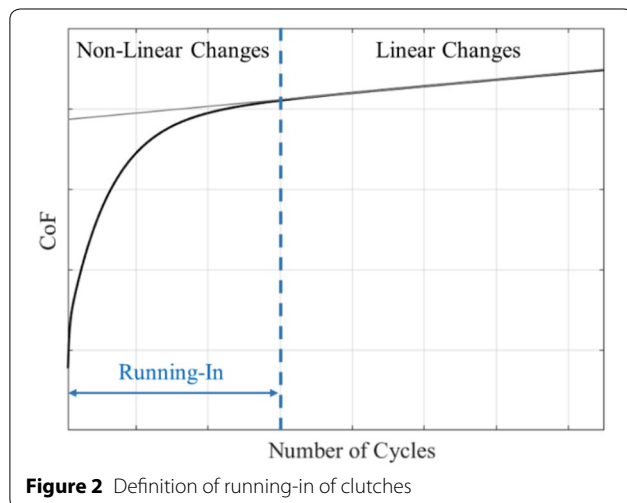
Moreover, some research works deal with the change in surface topography and real area of contact in the phase of running-in. The research group led by Takayuki Matsumoto carried out extensive investigations on the running-in behavior in connection with total reflection measurements of the real contact surface of a paper friction surface [29]. The measurements show a clear increase in the real contact area during running-in. Ingram et al. [30] made comparable observations by interference measurements. In Ref. [31] we simulated the real area of contact between a steel plate and a paper friction lining. The real area of contact is larger for a run-in friction pairing than for the new state.

Voelkel *et al. Chin. J. Mech. Eng.* (2020) 33:34

Page 3 of 9

Research works on the influence of the running-in phase on the performance of the run-in clutch are not known.
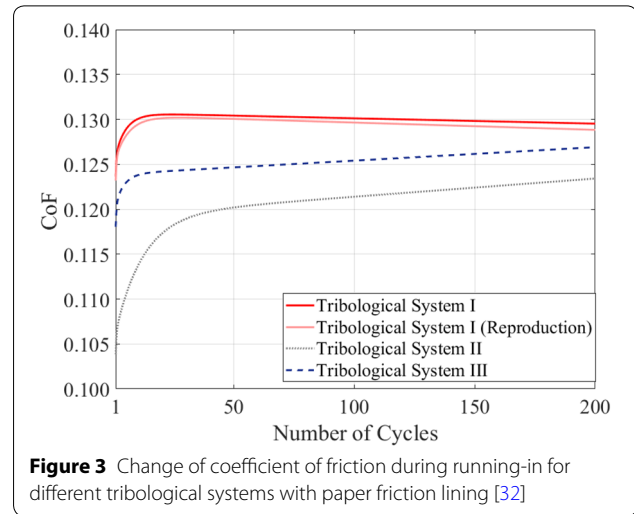
The characteristics and amount of changes in friction depend on the tribological system including the operating conditions. Until now, no clear definition of running-in of wet multi-plate has been given. As part of our research work, we established a general definition for running-in of a clutch in Ref. [32]: As long as the clutch shows non-linear changes in friction behavior, it is still running-in. As soon as these changes in friction derive a linear progress, the clutch is run-in (also see Figure 2). This definition takes requirements of practical application into account, as linear changes are easy to control, while non-linear changes may be challenging for clutch actuation.

Figure 3 shows the development of coefficient of friction CoF over number of cycles for clutches with three different tribological systems I, II and III with different fluids and paper friction linings of DCT and AT application. At the beginning of use, non-linear changes in friction occur. This phase is defined as the running-in of the clutch. Depending on the tribological system, degree and duration of the non-linear sections differ: With tribological systems I and III, non-linearities in friction behavior last less than 25 cycles, while tribological system II runs about 50 cycles before it gains linear changes in friction behavior.

Changes in friction behavior during running-in are mainly caused by the formation of chemical boundary layers in the friction contact and smoothing of surfaces. Figure 4 shows surface pictures of a steel plate in new condition and a steel plate after running-in recorded with a scanning electron microscope (SEM). Smoothing and therefore a decrease of surface roughness of the run-in

Figure 3 Change of coefficient of friction during running-in for different tribological systems with paper friction lining [32]

surface compared to the new surface is clearly visible and can also be measured.

3 Test Method to Investigate Running-In Behavior of Wet Multi-plate Clutches
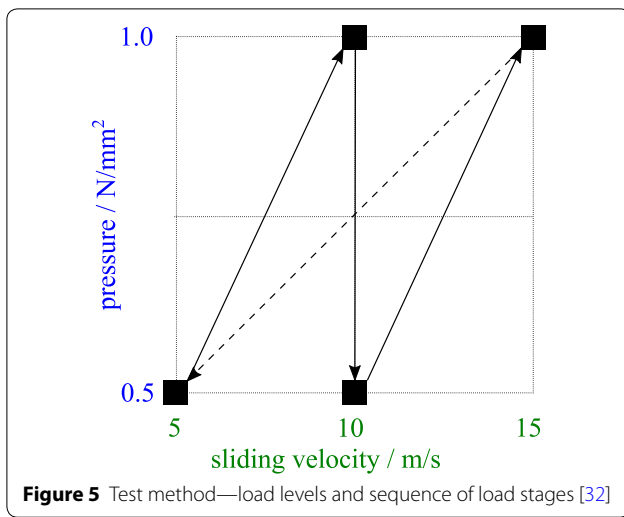
As of today, friction and running-in behavior of wet multi-plate clutches can only be investigated by experiment. To determine the running-in behavior of wet multi-plate clutches, we have elaborated a new test method. This test method introduces a test procedure to characterize the running-in behavior on different load levels. Furthermore, we submit a multi-stage procedure to evaluate and characterize the running-in behavior of clutches with mathematical approaches and new characteristic values.

3.1 Test Procedure
The objective of the test procedure is to be able to characterize the running-in behavior of the clutch on different load levels. To achieve this, we have defined a load spectrum consisting of four load stages (variation of pressure and sliding velocity). Figure 5 shows specific pressure and sliding velocity values of the four load stages. The test procedure is given by a single power shift on each load

Figure 2 Definition of running-in of clutches
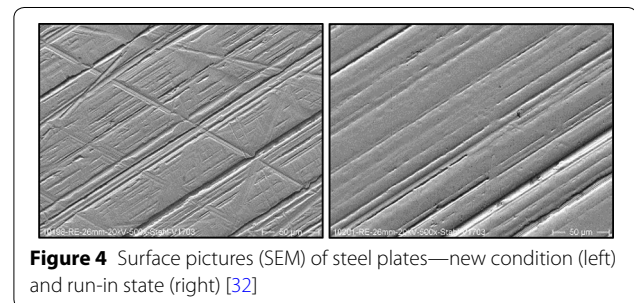
Figure 4 Surface pictures (SEM) of steel plates—new condition (left) and run-in state (right) [32]

Voelkel *et al. Chin. J. Mech. Eng.*   (2020) 33:34

Page 4 of 9

Figure 5 Test method—load levels and sequence of load stages [32]

**Figure 6** Method for characterization of running-in behavior

stage, sequence shown in Figure 5. A test to investigate running-in behavior consists of numerous repetitions of this sequence. Number of repetitions needed for investigation of the whole running-in is given by the criterion given in Section 2: Running-in is finished when changes in friction behavior are no longer non-linear but linear. It is recommended that one longer test be run first to ensure that changes in friction behavior are in fact linear. Quantitative criteria to evaluate the number of needed repetitions are given in Section 3.2. During our investigations, we ran 200 repetitions of the sequence consisting of four load stages each.

3.2 Characterization of Running-In Behavior
To be able to compare the running-in behavior of different clutches, e.g., with various fluids, steel plates and paper friction materials, a quantitative method for characterization is needed. Therefore we have defined a multi-stage procedure to evaluate running-in behavior of clutches (see Figure 6). Friction behavior is described by friction curve, characteristic friction values and trend plots (see Section 3.2.1). To describe the development of friction behavior during running-in, we have developed a mathematical equation and use regression analysis to elaborate compensating curves for trends of coefficient of friction CoF (see Section 3.2.2). As a last step of evaluation, we defined new characteristic values that allow a quantitative characterization of running-in behavior (see Section 3.2.3).

3.2.1 Friction Curve, Characteristic Friction Values and Trend of CoF
Friction behavior of wet multi-plate clutches is typically given by friction curve and characteristic friction values. A friction curve shows the values of CoF over sliding velocity.
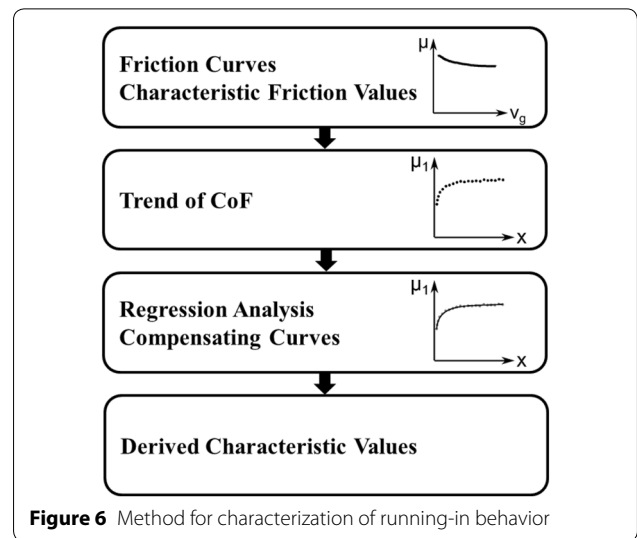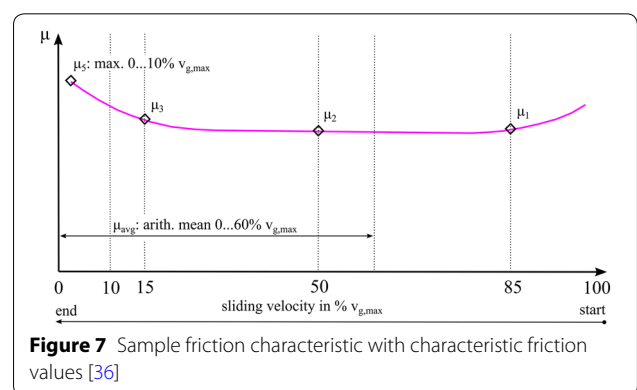
On a friction curve, characteristic friction values μ_1 to μ_5 and μ_{avg} are given according to Figure 7. These characteristic friction values are recognized values and are used in numerous scientific works on wet multi-plate clutches (e.g., Refs. [5, 20, 33–35]).
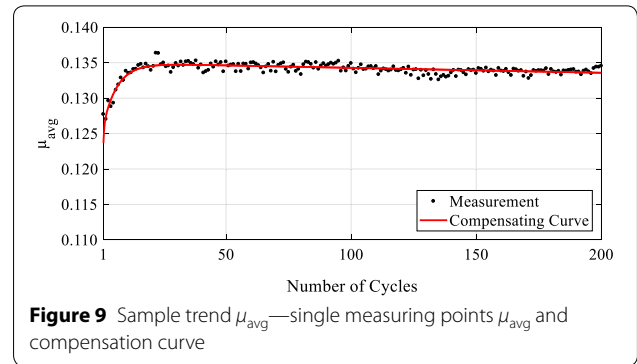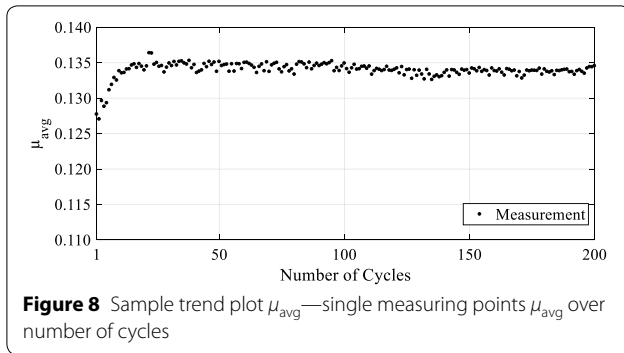
For each cycle of a test, a friction curve and the characteristic values are evaluated. By plotting the characteristic values over the number of cycles, friction trends are generated. Figure 8 shows an exemplary trend plot μ_{avg}. The friction behavior changes from cycle to cycle and shows variations and deviations due to physical phenomena.

3.2.2 Describing Trend Plots of CoF by Compensating Curves
To reach a quantitative description of the friction development during running-in, we have developed a parametrizable Eq. (1) to characterize progression and level of the friction coefficient at the beginning of use [32]:

$$\mu_{avg} = a - b^{x+c} + d \cdot (x - 200), \tag{1}$$

Figure 7 Sample friction characteristic with characteristic friction values [36]

Voelkel *et al. Chin. J. Mech. Eng.*   (2020) 33:34

Page 5 of 9

Figure 8 Sample trend plot μ_{avg}—single measuring points μ_{avg} over number of cycles

Figure 9 Sample trend μ_{avg}—single measuring points μ_{avg} and compensation curve

Table 1 Explanation of regression parameters of Eq. (1)

Parameter	Description
x	Number of cycles
a	Friction level at end of test ($x = 200$)
$-b^{x+c}$	Increase of friction at begin of test (non-linear section)
$d \cdot (x - 200)$	Slope in linear section

Table 2 Regression parameters (values) for compensating curve in Figure 9

Parameter	Value
a	0.134
b	0.837
c	25.62
d	-6.95×10^{-6}

By choosing the parameters *a*, *b*, *c* and *d* in a regression analysis, this equation can describe different friction trend plots of various tribological systems (e.g., as shown in Figure 3) by compensating curves.

Table 1 gives an overview and description of the regression parameters and terms of Eq. (1). The parameter *x* is the number of cycles and therefore greater than 0. The term $a + d \cdot (x - 200)$ describes the linear (run-in) section of the friction trend with *d* as the slope of the line and *a* as the friction level at the end of test ($x = 200$). The non-linear part at the beginning of test is mathematically represented by the term $-b^{x+c}$. The parameter *b* influences the slope of the curve and its radius of curvature: small values for *b* lead to high slopes and small radii of curvature and the other way round. By choosing parameter *c*, the angular point of the curve is shifted to the left ($c > 0$) or right ($c < 0$). With values for *b* between 0 and 1, the curve described by the term $-b^{x+c}$ is strictly increasing and converges towards zero with increasing *x*. To determine optimized parameters *a*, *b*, *c* and *d*, the method Least Absolute Residuals (LAR) is used for optimization. With this method, single outliers in CoF (e.g., caused by interruption of test for measurements or due to failure) affect the optimization less as residuals are not squared as in the least squares method.

Figure 9 shows the compensating curve for the trend plot μ_{avg} given in Figure 8. The compensating curve is given by Eq. (1), the parameters *a*, *b*, *c* and *d* are determined by regression analysis (explained above) to the
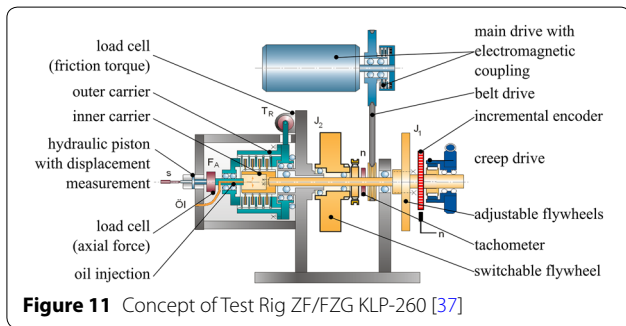
values given in Table 2. In the clearly non-linear section at the beginning of the friction trend plot (about first 20 cycles) the compensating curve has a steep rise and a small radius of curvature given by a comparatively small value for parameter *b*. The positive value for *c* indicates a shift of the curve to the left. The comparatively small but negative value for *d* expresses the slightly downward trend of μ_{avg} in the linear section of the trend plot ending up at a friction level of round about 0.134 represented by the parameter *a*.

3.2.3 Characteristic Values to Describe Running-In Behavior

Running-in behavior of a clutch with paper friction lining is characterized by non-linear changes of the friction behavior. When changes in friction behavior become linear, the clutch is defined as run-in (see Section 2). Eq. (1) describes the running-in behavior of clutches mathematically. When the term $-b^{x+c}$ diverges to zero, the friction curve segues into its linear section and the running-in of the clutch is finished. As the significance of the term $-b^{x+c}$ is limited, we have developed pursuing characteristic values to describe changes of coefficient of friction at the beginning of the lifetime. The number of cycles run before the friction curve changes to a linear characteristic (and the term $-b^{x+c}$ diverges to zero) is described by the value x_{lin}. The change of coefficient of friction from the beginning of the lifetime to cycle x_{lin} is expressed by the characteristic value $\Delta\mu_{start}$. Figure 10 visualizes the characteristic values x_{lin} and $\Delta\mu_{start}$.

Voelkel *et al. Chin. J. Mech. Eng.*   (2020) 33:34

Page 6 of 9
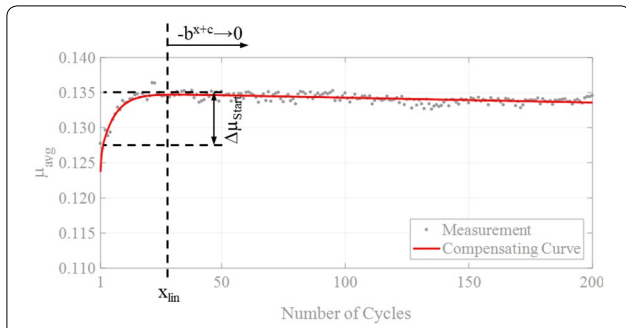
Figure 10 Sample trend plot μ_{avg} with derived characteristic values x_{lin} and $\Delta\mu_{start}$

Figure 11 Concept of Test Rig ZF/FZG KLP-260 [37]

Figure 12 Test parts—steel plate (left), friction plate with DCT friction material (middle), friction plate with AT friction material (right)

Figure 13 Sample friction trend plot μ_{avg} with compensating curve and residuals for tribological system I

Requirements for safe and comfortable actuation of the clutch are small changes in friction behavior and therefore low levels for the characteristic values x_{lin} and $\Delta\mu_{start}$.

4 Test Rig, Test Parts and Fluids

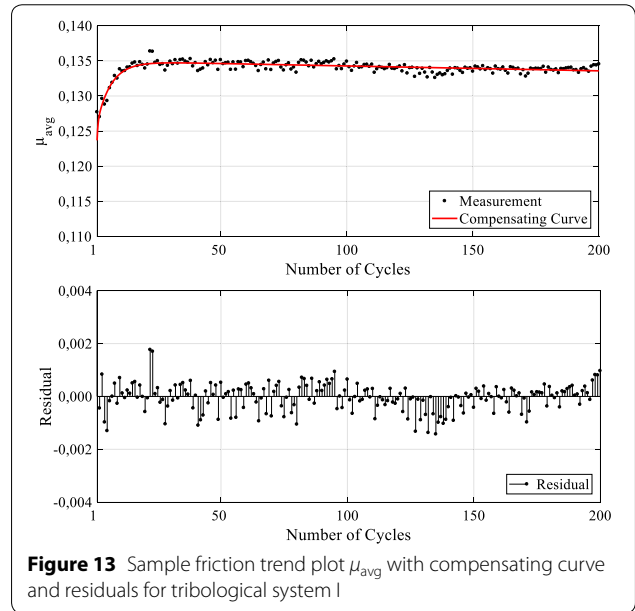### 4.1 Component Test Rig ZF/FZG KLP-260

The tests are performed on the standard component test rig ZF/FZG KLP-260 [37], as component testing is very efficient while also being easily transferred to practical application. The test rig ZF/FZG KLP-260 (Figure 11) operates in braking mode, the outer carrier is fixed and the inner carrier rotates. In power shift mode, the main shaft is accelerated by the main drive. The clutch is actuated by a hydraulic piston in a force-controlled mode. Axial force, difference in rotational speed, displacement and friction torque are measured, and coefficient of friction is calculated online.

4.2 Test Parts and Fluids

The experimental investigations are carried out with clutches of the same size ($d_A/d_I = 170/196$ mm; six friction interfaces) under variation of friction material and fluid. As friction materials, typical paper friction linings from DCT and AT application are used. Fluids

are typical serial fluids from DCT and AT application (see Figure 12).

5 Results and Discussion

We applied the test method described in Section 3 on three different tribological systems I, II and III (see Figure 3). System I is a typical DCT application (DCT friction material, DCT fluid), System II a typical AT application (AT friction material, AT fluid). System III represents a DCT fluid with an AT friction material and therefore is no series application.

With each tribological system I, II and III we ran tests on the component test rig ZF/FZG KLP-260. In each test, we interrupted the test after 20 cycles and 100 cycles. Evaluating the friction behavior of the clutches, we get friction trend plots for each of the four load stages given in Figure 5. In a regression analysis, we describe these friction trends with compensating curves given by Eq. (1). Characteristic values x_{lin} and $\Delta\mu_{start}$ are derived to reach a quantitative description of the running-in behavior of the three different tribological systems. In Figures 13, 14, 15, we show the friction trend plots for the
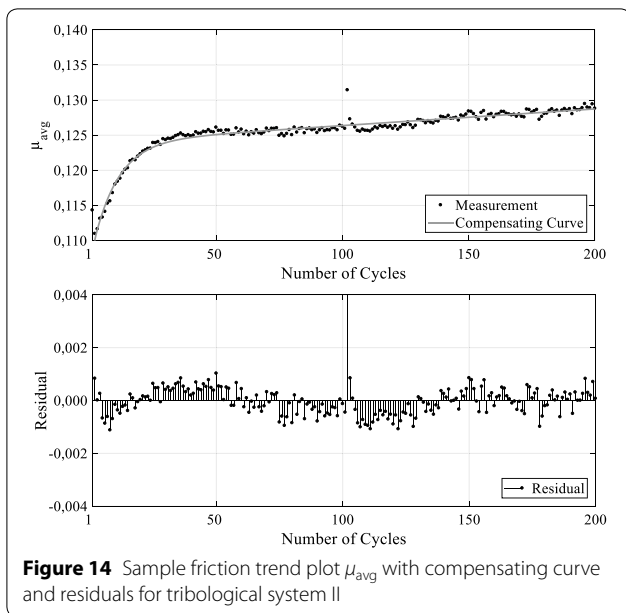
Voelkel *et al. Chin. J. Mech. Eng.*   (2020) 33:34

Page 7 of 9

Figure 14 Sample friction trend plot μ_{avg} with compensating curve and residuals for tribological system II
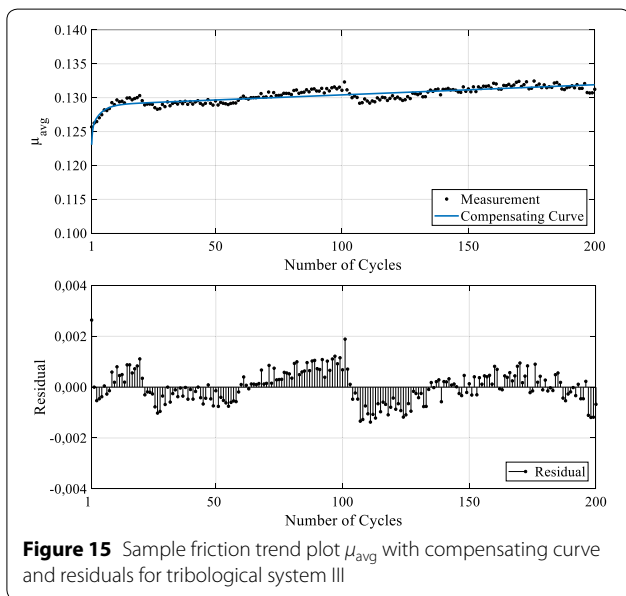

Figure 15 Sample friction trend plot μ_{avg} with compensating curve and residuals for tribological system III

three tribological systems on one sample load stage. Single outliers in CoF occur due to interruption of test at cycles 20 and 50. For each tribological system, the regression parameters a, b, c and d and the characteristic values x_{lin} and $\Delta\mu_{start}$ are given in Table 3. Besides the compensating curves we evaluated the residuals of measurement and compensating curve for each cycle. The statistical values R^2 and $\bar{R}$ are also given in Table 3.

According to the definition of running-in given in Section 2, the system III shows the shortest running-in and therefore the best running-in behavior: The section

with non-linear changes in friction behavior is short and slightly pronounced, the clutch quickly reaches a linear friction behavior. This behavior is also displayed by the regression parameters b and c (small value for b and small positive value for c) and—more striking—by the characteristic values x_{lin} and $\Delta\mu_{start}$, that are both comparatively low. As the tribological system III is not a series application, reconditioning of friction behavior after interruptions of test (cycles 20 and 50) is quite pronounced. This is also expressed by a comparatively low value for R^2 in Table 3. System II takes the longest until it is run-in (high values for b and c and x_{lin}): with $x_{lin} = 44$, running-in lasts more than four times longer than with system III. Changes in CoF during running-in are also much stronger with system II than with system III. This is clearly shown by a significantly higher value $\Delta\mu_{start}$ for system II. In the linear (run-in) section of the friction trend plot, system I shows a negative slope while systems II and III show differing but both positive slopes. This behavior is clearly given by different values for regression parameter d. Differences in friction behavior at the end of test are given by parameter a. For all systems, the mean amount of residuals is very low (< 0.5 %), what shows the high quality of the regression analysis.

6 Conclusions

Wet multi-plate clutches with paper friction linings show distinct changes in friction level and progression due to running-in processes at the beginning of the lifetime. The more pronounced these changes in friction behavior are, the more challenging safe and comfortable actuation of a clutch can be. Therefore, it is important to be able to systematically investigate and characterize the running-in behavior of wet multi-plate clutches.

In this paper, we introduce a clear definition for running-in of a clutch: Running-in of a clutch is characterized by non-linear changes in friction behavior. A clutch is run-in as soon as these changes in friction derive a linear progress. This definition takes requirements of practical application into account, as linear changes are easy to control, while non-linear changes may be challenging for clutch actuation.

To systematically investigate the running-in behavior of wet clutches, we have elaborated a new test method. This test method introduces a test procedure to characterize the running-in behavior on different load levels. Tests are performed as component tests on the standard test rig ZF/FZG KLP-260. We submit a multi-stage procedure to evaluate and characterize the running-in behavior of clutches. The friction behavior of the clutch is evaluated by friction curve, characteristic friction values and trend plots. To describe the development of friction behavior

Voelkel *et al. Chin. J. Mech. Eng.* (2020) 33:34

Page 8 of 9

Table 3 Running-in behavior of different tribological systems: results of test method being introduced in Section 3

Tribol. system	Parameter			
	a	*b*	*c*	*d*
I	0.134	0.837	25.62	-6.95×10^{-6}
II	0.129	0.903	39.85	23.69×10^{-6}
III	0.132	0.759	19.61	14.99×10^{-6}
Tribol. system	Parameter			
	x_{lin}	$\Delta\mu_{start}$	R^2	$\bar{R}$
I	23	0.007	0.979	0.0004
II	44	0.014	0.996	0.0005
III	10	0.003	0.716	0.0006

during running-in, we have developed a mathematical equation and use a regression analysis to elaborate compensating curves for friction trends. Newly defined characteristic values x_{lin} and $\Delta\mu_{start}$ allow a quantitative characterization of running-in behavior.

The quality of the test procedure is demonstrated by the example of three different tribological systems from DCT and AMT application using paper friction linings. We are able to rate the running-in behavior of the three systems using the given definition of running-in and show how this rating is displayed by mathematical equations and the new characteristic values x_{lin} and $\Delta\mu_{start}$.

Authors' Contributions
The research work has been carried out by Katharina Voelkel; she also wrote the manuscript. Hermann Pflaum and Karsten Stahl have accompanied, supported and supervised the work as head of department (Hermann Pflaum) and professor (Karsten Stahl). All authors read and approved the final manuscript.

Authors' Information
Dipl.-Ing. Katharina Voelkel, born in 1988, is head of the department "Disk Clutches" at *Gear Research Centre (FZG), Technical University of Munich, Germany*. She received her diploma from *Technical University of Munich, Germany*, in 2013 and finished her PhD studies in 2019. Her research interests include functional behavior of disk clutches including running-in behavior, influences of tribological system on the friction behavior, and thermal behavior.

Dr.-Ing. Hermann Pflaum, born in 1955, is head of the department "Clutches and Mechanical Drive" at *Gear Research Centre (FZG), Technical University of Munich, Germany*.

Prof. Dr.-Ing. Karsten Stahl, born in 1969, is full professor and director of *Gear Research Centre (FZG), Technical University of Munich, Germany*.

References
[1] H Czichos, K-H Habig. *Handbook of tribology – tribometry, tribomaterials and tribotechnics*. 4th ed. Wiesbaden: Springer Vieweg, 2015. (in German)
[2] T Ichihashi. Recent developments in lubricating oils for wet clutches and wet brakes. *Japanese Journal of Tribology*, 1994, 39: 1461–1470.
[3] R Mäki, B Ganemi, R Olsson, et al. Wet clutch transmission fluid for AWD differentials: influence of lubricant additives on friction characteristics. *Lubrication Science*, 2007, 19: 87–99.
[4] M Ingram, J Noles, R Watts, et al. Frictional properties of automatic transmission fluids: Part I—Measurement of friction-sliding speed behavior. *Tribology Transactions*, 2010, 54(1): 145–153.
[5] U Stockinger, K Muehlenstrodt, K Voelkel, et al. Investigation of tribological layers with time-of-flight secondary ion mass spectrometry (ToF-SIMS)—Additive's influence on friction behavior of wet multi-plate clutches. *Engineering Research*, 2019, 83: 219–226. (in German)
[6] P Nyman, R Mäki, R Olsson, et al. Influence of surface topography on friction characteristics in wet clutch applications, *Wear*, 2006, 261: 46–52.
[7] M Bäse, M Dzimko, L Deters. Empirical evaluation of relations between finishing parameters and frictional behavior of friction clutch pairings in microslip operation. *Proceedings of 57. Tribologie-Fachtagung*, Goettingen, Germany, 26.-28.09.2016. (in German)
[8] P Marklund, R Mäki, R. Larsson, et al. Thermal influence on torque transfer of wet clutches in limited slip differential applications. *Tribology International*, 2007, 40: 876–884.
[9] B-R Hoehn, H Pflaum, C Mosbach. Methodology for assessing the influence of lubricant on the frictional vibration behavior of wet multi-plate clutches. *VDI-Berichte No. 1786*, 2003: 455–468. (in German)
[10] W Ost, P de Baets, J Degrieck. The tribological behaviour of paper friction plates for wet clutch application investigated on SAE# II and pin-on-disk test rigs. *Wear*, 2001, 249: 361–371.

Voelkel *et al. Chin. J. Mech. Eng.*   (2020) 33:34

Page 9 of 9

[11] K Ito, K Fujimoto, M Eguchi, et al. Friction characteristics of a paper-based facing for a wet clutch under a variety of sliding conditions. *Tribology Transactions*, 1993, 36: 134–138.

[12] R C Lam, Y F Chen. Friction material for continuous slip torque converter applications: Anti-shudder considerations. *SAE Transactions*, 1994, 103: 1445–1455.

[13] M T Devlin, S H Tersigni, J Senn, et al. *Effect of friction material on the relative contribution of thin-film friction to overall friction in clutches.* SAE Technical Paper No. 2004-01-3025, 2004.

[14] M Katsukawa. *Effects of the physical properties of resins on friction performance.* SAE Technical Paper No. 2019-01-0341, 2019.

[15] E Abbott, F A Firestone. Specifying surface quality: A method based on accurate measurement and comparison. *ASME Journal of Mechanical Engineering*, 1933, 55: 569–572.

[16] P J Blau. Interpretations of the friction and wear break-in behavior of metals in sliding contact. *Wear*, 1981, 71: 29–43.

[17] P J Blau. On the nature of running-in. *Tribology International*, 2005, 38: 1007–1012.

[18] D J Schipper. *Transitions in the lubrication of concentrated contacts.* Enschede: University of Twente, 1988.

[19] J D Summers-Smith. *An introductory guide to industrial tribology.* London: Mechanical Engineering Publication, 1994.

[20] U Stockinger, H Pflaum, K Stahl. Efficient friction screening method for wet multiple disk clutches with carbon friction material. *Engineering Research*, 2018, 82: 1–7. (in German)

[21] M Bezzazi, A Khamlichi, A Jabbouri, et al. Experimental characterization of frictional behaviour of clutch facings using Pin-on-disk machine. *Materials and Design*, 2007, 28(7): 2147–2153.

[22] E Zhao, B Ma, H Li. The tribological characteristics of Cu-based friction pairs in a wet multidisk clutch under nonuniform contact. *ASME Journal of Tribology*, 2018, 140(1), https://doi.org/10.1115/1.4036720.

[23] J Pokorny. *Investigation of the friction processes in clutches with friction plates made of steel and sintered metal.* Stuttgart: Technische Hochschule Stuttgart, 1960. (in German)

[24] J Duminy. *Assessment of the operating behavior of shiftable friction clutches.* Berlin: Technische Universität Berlin, 1979. (in German)

[25] F Pfleger. *Functional and endurance behavior of wet multi-plate clutches.* Munich: Technische Universtität München, 1998. (in German)

[26] B-R Hoehn, H Pflaum, F Pfleger. *Methodology for assessing the influence of lubricant on the frictional vibration behavior of wet multi-plate clutches.* VDI-Berichte No. 1610, 2001: 575–592. (in German)

[27] M Yesnik, R C Lam. *Clutch plate surface treatment for improved frictional characteristics.* SAE Technical Paper No. 922099, 1992.

[28] Q Zou, C Rao, G Barber, et al. Investigation of surface characteristics and tribological behavior of clutch plate materials. *Wear*, 2013, 302: 1378–1383.

[29] Z Huang, S Aihara, S Umezawa, et al. A study on running-in mechanism of paper-based friction material for a wet clutch: consideration based on measuring the surface profile and the real contact area by total reflection method. *Japanese Journal of Tribology*, 1997, 42: 375–384.

[30] M Ingram, H Spikes, J Noles, et al. Contact properties of a wet clutch friction material. *Tribology International*, 2010, 43: 815–821.

[31] K Voelkel, M Rothemund, S Albarracin-Garibello, et al. On the simulation of the micro-contact of rough surfaces using the example of wet friction clutch materials. *Lubricants*, 2019, 7: 41ff.

[32] K Voelkel, H Pflaum, K Stahl. Running-in behavior of wet multi-plate clutches—investigation and characterization. *Proceedings of Asia International Conference on Tribology*, Kuching, Malaysia, 17–20.09.2018: 19–20.

[33] G J Meingaßner, H Pflaum, K Stahl. *Friction behavior of wet multi-plate clutches at the transition from static to sliding friction.* VDI-Berichte No. 2309, 2017. (in German)

[34] K Voelkel, H Pflaum, K Stahl. Influences of the steel plate on the running-in behavior of wet multi-plate clutches. *Engineering Research*, 2019, 83: 185–197. (in German)

[35] T Schneider, H Pflaum, K Stahl. Spontaneous damage behavior of wet mulit-plate clutches with organic and metallic friction lining. *Engineering Research*, 2019, 83: 199–207. (in German)

[36] B Hämmerl. *Endurance and temperature behavior of wet multi-plate clutches under collective load.* Munich: Technische Universität München, 1995. (in German)

[37] G J Meingaßner, H Pflaum, K Stahl. Test-rig based evaluation of performance data of wet disk clutches. *Proceedings of 14th International CTI Symposium*, Berlin, 7–10.12.2015. (in German)