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Thermal and thermoelastic problems in dry friction clutch: A comprehensive review

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Abstract

The friction clutch is considered a very important element of machines, as it plays a major role in transferring power from the driving part to the driven part. A common application of the friction clutch is in vehicles to connect between the gearbox and the engine. Fast wear occurs as a result of frictional heating that is generated when the clutch is starting to engage. This wear, in addition to the high thermal stresses, will lead to premature failure in the contacting surfaces. The present review highlights the most important studies of the thermal and thermoelastic problems of friction clutches during the last 10 years to show the challenges that were overcome and also the other challenges that needed to find solutions. The present paper will discuss in detail the influence of the frictional heat generated between contact surfaces during slipping and the main factors affecting the thermal behavior of dry friction clutches, such as sliding speed, friction materials, applied pressure, and so on. Furthermore, significant conclusions and remarks based on the available solutions to the thermal problem of the clutch are presented.

KEYWORDS

dry friction clutch, thermal problem, thermoselastic problem

1 | INTRODUCTION

The clutch is one of the most important components of vehicles that performs a vital function in transmitting power and motion from one part to the other. The main role of the clutch is to disconnect and reconnect the drive part and the moving part, in other words, connect between the engine and the gearbox. The main components of the friction clutch through which it performs its functions are the flywheel, clutch disc, and pressure plate as shown in Figure 1.[1] The frictional heat generation leads to a very fast increase in temperature and thermal stresses in the contacting elements of the clutch system. The thermal problem due to friction is complex because it includes many different factors and requires deep study and analysis. Often, when temperatures exceed their permissible values, they lead to harmful effects, such as thermal cracks, fluctuations in the coefficient of friction, deterioration of the friction material, and significant thermal deformations.[2] Figure 2 illustrates the process of idealized moving-off for the friction clutch, where t_s represents slip time while torque is T. During the sliding period, the first period will start due to the difference in speeds between the contact surfaces. The slip occurs as the clutch begins to engage with other elements. After this period, the full shift period (second period) begins when all elements of the clutch system rotate at the same speed without slip. During the first period, a large amount of energy is transformed from kinetic form to thermal caused by slipping. There is another load caused by contact pressure between the contact surfaces due to the applied force as shown in Figure 2B, which explains the load conditions during the friction clutch engagement cycle. There are three types of loads: the thermal effect during the first period (the slip period), the pressures between the contact surfaces due to the axial force, and the centrifugal force resulting from the rotation of the clutch element.[1]

2 | FAILURE PATTERNS IN THE FRICTION CLUTCH

There are several types of failure that can accompany the clutch operation that can affect the functioning and performance of the friction clutch system. Thermal failure is the most important type, due to its direct effect and the great possibility of its occurrence. This category

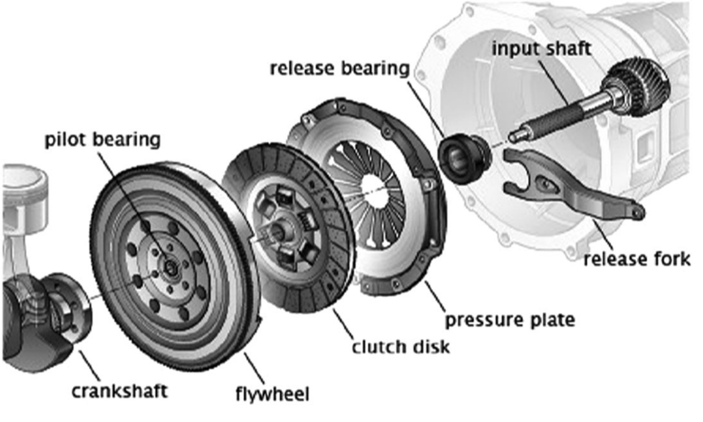

FIGURE 1 The parts of the friction clutch system (single-disc clutch)[3]

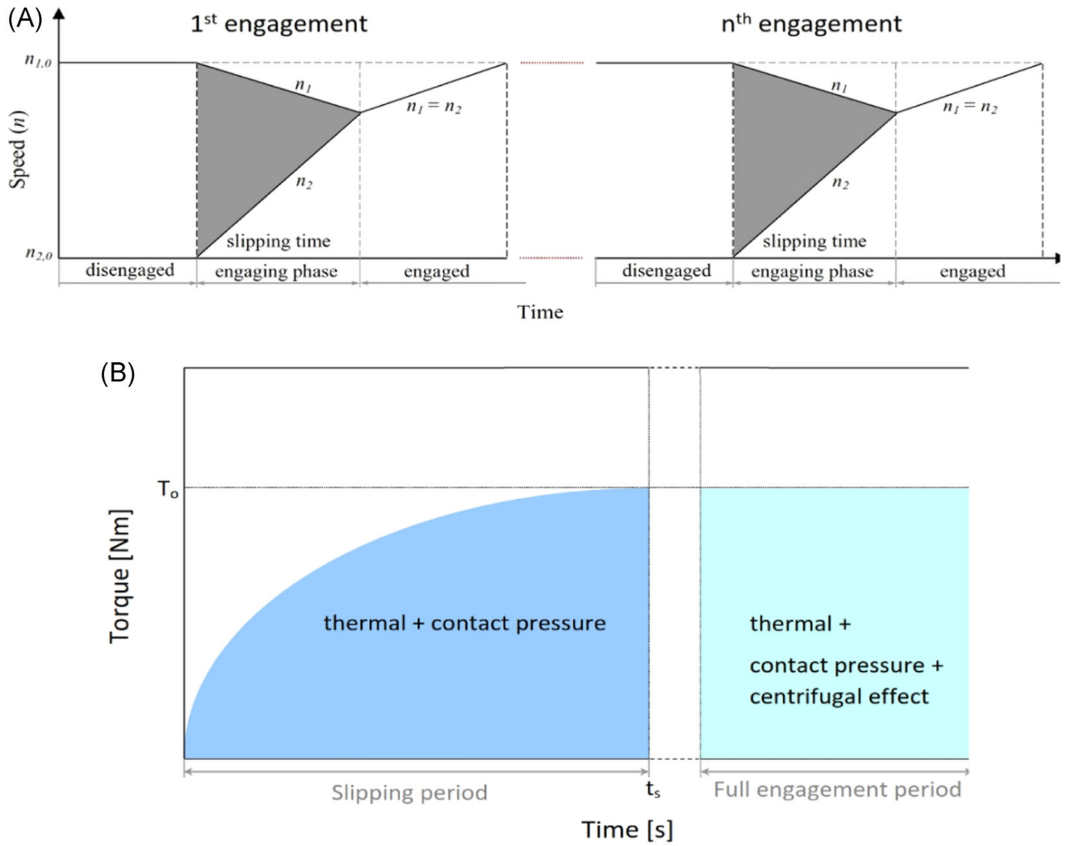

FIGURE 2 (A) Process of idealized moving-off for the friction clutch. (B) The load conditions during the engagement cycle of the clutch[1]

includes several types, such as dishing, waviness or buckling, banding or crushing, material transfer, bond failure, burst failure, grooving, reduced performance, and distortion. The previous types are the result of excessive heat generation in which the metal surface of the clutch is unable to expel it outside the system. In turn, it will contribute along with other factors to lead the sliding system, to reach the point of failure. High contact pressure leads to heat concentration in a small zone of the contact area, subsequently leading to high thermal stresses.[4] Figure 3A shows the effects of thermal failure on the friction clutch disc and pressure plate, where the hot spot occurred due to the high contact pressure and heat generation, which led to high thermal deformations in the form of a small zone. Figure 3B shows a block diagram that explains the main variables that affect the thermal behavior, which may lead to failure in the end under specific conditions.

The present paper aims to make a comprehensive review concerning the available solutions and the challenges that need solutions for the thermal and thermoelastic problems in friction clutches. The approaches that have been used for the last 10 years to analyze the coupling problem to find the thermal stresses in the element of friction clutch system will be described. In addition to identifying the most important variables that influence the behavior and performance of clutch systems, researchers presented samples of their findings based on various

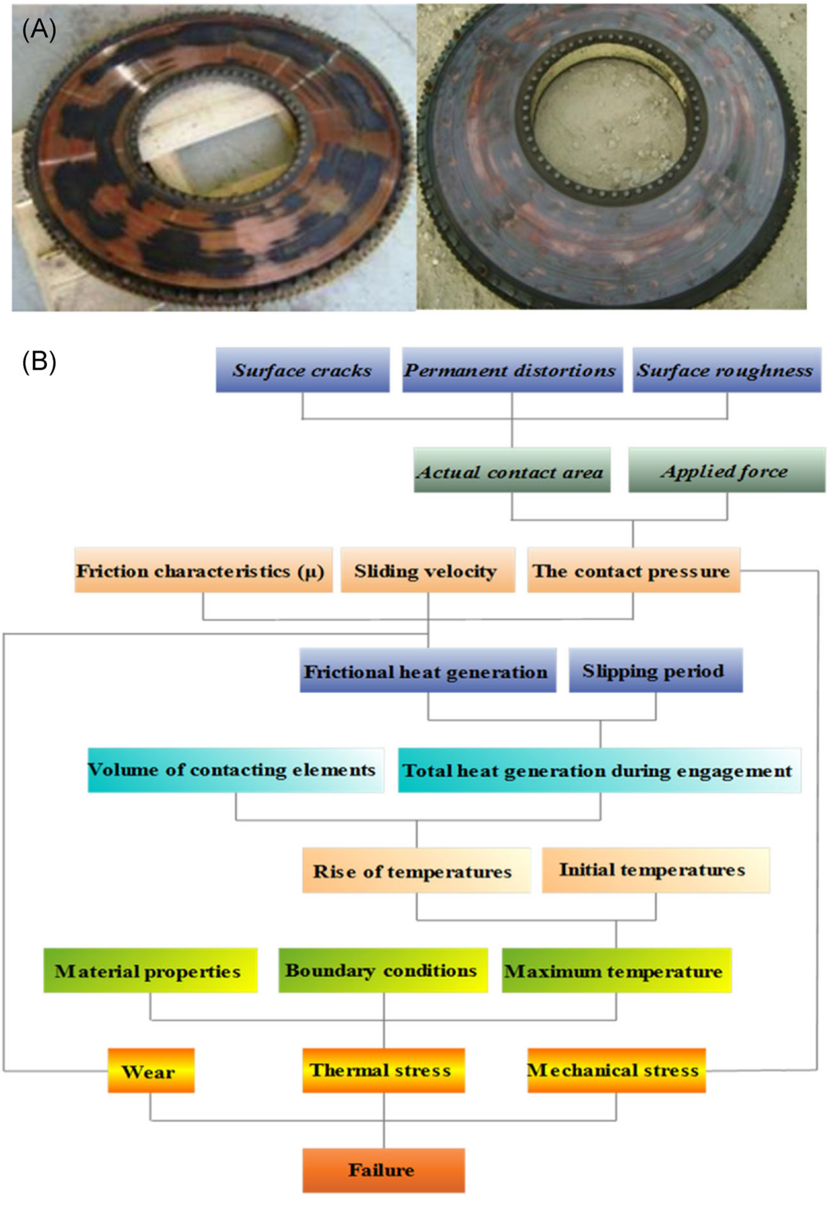

FIGURE 3 (A) Failure in the contacting surfaces due to thermal effects (hot spots).[5] (B) Flowchart of finite element simulation of sequentially coupled thermal–mechanical approach[6]

approaches and assumptions. Finally, this paper will be a significant guide for future investigations of the thermal and thermoelastic problems of clutch systems.

2.1 | The energy balance of thermal analysis

During the sliding process, there will be a difference between the entry and exit energies. This energy difference will turn into heat loss, which will cause the clutch parts to heat up. Figure 4 shows the energy process during the sliding period of the friction clutch disc. The system is heating up faster due to the frequent launches, which will increase the rate of heat generation. The amount of heat generated during slip can be calculated according to the energy balance of the friction clutch disc as shown in Figure 5[7]:

$$Q_{Conv.} = Q_{gen.c} - Q_{Int.enrg.};\ t > 0, \tag{1}$$

$$\Delta Q_{Int.energ.} = \rho cv(T_{t+\Delta t} - T_t),\ t > 0. \tag{2}$$

When substituting Equation (2) into Equation (1), we obtain

$$Q_{Conv.} = Q_{gen} - \rho cv(T_{t+\Delta t} - T_t);\ \mathrm{t} > 0. \tag{3}$$

The internal energy of the clutch disc at any time is

$$\Delta Q_{Int.energ.} = \Delta Q_{I.int.energ.} + \Delta Q_{Int.energ.} = \rho cv T_{t+\Delta t};\ \mathrm{t} > 0, \tag{4}$$

where $Q_{conv.}$ represents the heat transfer by convection, $Q_{gen.}$ is the energy generated during the slipping period, $Q_{Int.enrg.}$, and $Q_{I.\ int.energ.}$ is the initial internal energy of the clutch disc.

3 | THERMOELASTIC ANALYSIS OF SLIDING CONTACT

Contact problems will occur when the surfaces of clutch elements press together, and a high amount of frictional heat will be generated due to sliding at the beginning of an engagement. Owing to the frictional heating that appears in the contacting elements, the coupling between the mechanical and thermal mechanisms has a great influence on the temperature and thermal stresses in the contact area. One of the decisive negative results of the coupling problems in a sliding system, such as brakes and clutches is the wear, high thermal stresses, deformations, and instability of the system due to the excessive temperature.[10] It must be emphasized that the

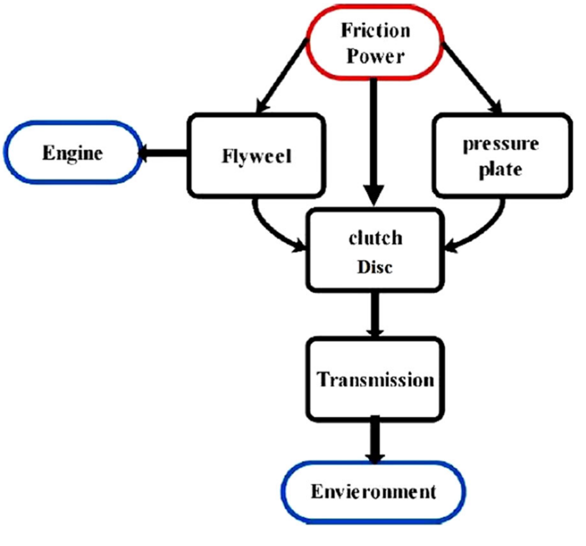

FIGURE 4 The components of the dry clutch system[8]

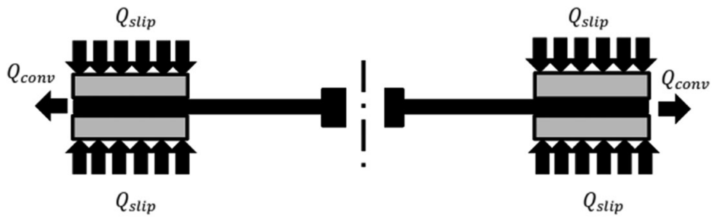

FIGURE 5 The energy balance of the friction clutch disc during the sliding process[9]

proof of the classical existence and uniqueness of thermal conductivity and thermal elasticity do not apply to this problem. If we know the temperature range, there will be a unique solution to the communication problem and the opposite.

Therefore, it should be that automotive designers have sufficient knowledge about the available solutions to thermoelastic problems in friction clutches. For example, the amount of heat that will be stored in the friction clutch can be reduced when frictional facing with good thermal properties are used instead of the most available ones that have very poor thermal properties. This will lead to reducing the magnitudes of the thermal stresses based on the results of Barber et al.[8,11–13] They studied thermal contact problems in more than one aspect. It was investigated by transient and stable analyses, but the hypothesis was Hertzian approximation. The studies focused on achieving several goals, the most important of which is the description of the transient process with which pressure disturbance develops from a simple state until it reaches a state of contact. The studies found that if the result of dividing the initial contact radius by the radius of the radius at stability was relatively large, and depending on the thermal diffusion and the original contact radius, the rate of decrease in the radius would be linear with the passage of time. In addition, the subject was studied in References [14–24] through an integrated analysis of the phenomenon and some influencing parameters, such as sliding speed and applied pressure. Figure 6 depicts the coupling of the thermal and mechanical problems. Figure 7 illustrates the behavior of the maximum temperature with respect to time on the contact surfaces of a dry clutch during a single engagement. The curve gives a visualization of the surface temperature behavior during two phases: The first stage represents the sliding period (the heating period) and the second phase is known as the complete engagement (the cooling phase). When $t = 0$, the initial temperature (T_i) is equal to the surface temperature, then during the slipping period the temperature will reach the maximum value of T_{max} at ($0 < t_s < t$), after exceeding the slip period the temperature will drop to the value final (T_f).

4 | TRANSIENT THERMAL ANALYSIS

The importance of a transient solution comes from the fact that the engagement consumes a very short period of time that does not allow the system to reach a steady state. Therefore, it can be considered that the transient thermal solution is the optimal solution to the frictional heating problem during the sliding period. But on the other hand, there are some difficulties in finding the solution of the governing equations when including all the effective factors.

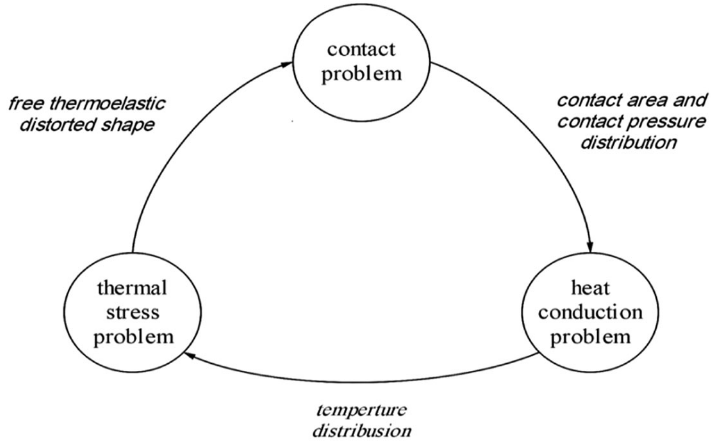

FIGURE 6 Coupling between the thermal and mechanical problems[10]

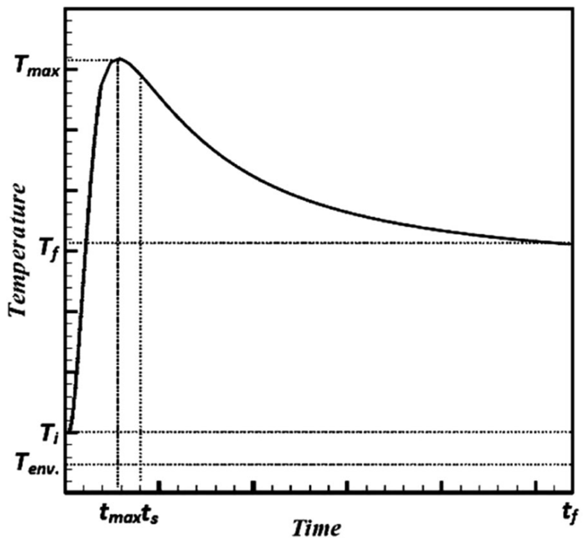

FIGURE 7 The behavior of surface temperature with time in the dry clutch[25]

Al-Shabibi and Barber[26] provided the transient solution to the problem of nonhomogeneous thermoelastic contact with frictional heating. Homogenous and particular solutions with appropriate initial and boundary conditions are used to solve the problem. A general solution was found by superposing the homogeneous temperature and the particular temperature:

$$T^i(t) = \sum_{k=1}^{n} C_k \hat{\theta}_i^k e^{b_k t} + \theta_p^i, \tag{5}$$

where n is the number of degrees of freedom, C_k is the constant that exists from the initial condition, θ_p^i is particle solution, $\hat{\theta}_i^k$ is eigenfunctions, and b_k is eigenvalues.

It was assumed, in this analysis, an optimal time-efficient scheme to obtain the required solution. Both solution parts tested many variables, such as constant, variable slip speed, and critical speed.

Li and Barber[27] developed previous solutions[26] by presenting a modern method for dealing with thermoelastic instability by developing a more efficient algorithm. The modern method is characterized by its high ability to overcome the problem of computer solution density, but it stipulates that the number of required solutions be limited to the specified number of speeds as well as communication conditions. The results showed the effectiveness of the solution used due to the high accuracy obtained.

Zagrodzki[28] focused on the method of transient model analysis and illustrated the mechanisms that trigger unstable patterns. For convenience, the analysis is performed at a constant sliding speed. The model developed by Li and Barber was used, as this model proved to be effective in analyzing and solving problems related to variable velocity. The study concluded that the combination of the background procedures with the ideal pressure distribution, which contributes to produce the deformation, leads the change the status of system to unstable situation. Whereas, the model used in the study of sliding surfaces also includes convection, which reflects a wide range of sliding systems and can include three-dimensional (3D) engineering without adding other complications to the solution. The model of transient analysis of the temperature distribution in a dry clutch was investigated. Figure 8 shows the temperature distributions at different time intervals by Zagrodzki.[28] The transient analysis took sufficient space within the research interest to try to complete all aspects related to the issue and to find the optimal possible solutions.[29–34]

5 | THERMOELASTIC ANALYSIS METHODS

In recent years, many researchers have investigated the solution to the thermoelastic problem for friction clutches. The numerical approach such as the finite element method was used mainly and fewer researchers used experimental work, while very limited researchers applied the analytical method.

Previously, the investigations were conducted experimentally. But after 1990, researchers started to apply computational techniques, where numerical techniques play a major role in the premanufacturing analysis. The most common computational technique used recently is the finite element analysis method.[30-36]

The main need of the industrial sector is to find reliable solutions with accepted accuracy to obtain a successful design that satisfies the thermal and mechanical requirements of the friction clutch system. This approach should include basic information, such as the value of the safe surface temperature, the maximum surface temperature, thermal stresses, rate of wear, and so on. Since it is very difficult to find the results with high accuracy because it requires direct measurements on the surface of the clutch to calculate the temperatures at any instant, which are often expensive and time-consuming, constructing a mathematical model with the use of assumptions based on the working conditions saves cost and time.[35] The process of building the mathematical solution is illustrated in Figure 9.

Entezari[38] studied the behaviors of both thermal and thermoelastic of frictional discs subject to the influence of thermal loads. He adopted two methods to solve the problems. The first method was represented by using an analytical solution to find solutions to the problems of thermal elasticity. As for the second method, it went toward developing an innovative and new mechanism for specific elements 1D with 3D capabilities and then using it for more complex problems where the analytical solution does not always work. The closed formulas for the domains related to temperature and displacement were deduced by adopting two types of

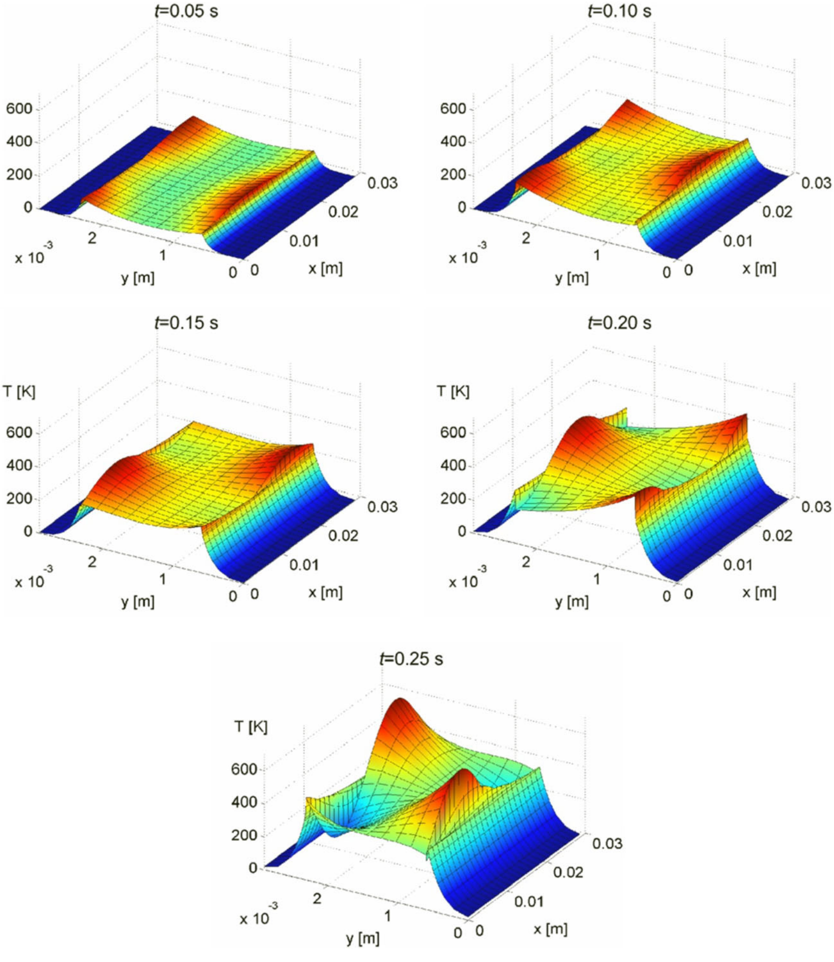

FIGURE 8 Distributions of the temperature of the friction clutch system at different times of the sliding period[28]

theories, the first group being the classical theories and the other theories, which are dynamic and quasi-static unconjugated. These solutions have been able to deal with different practical problems of thermal elasticity and are also very effective for many variables, such as distribution and time related to temperature, pressures, and so on. The presented study can be a starting point for investigating more complex issues such as thermoelastic taking into consideration the wear effect.

Abdullah et al.[39] analyzed the problem of thermoelastic of the multi-disc friction clutch using the finite element method. An accurate description of the problem was obtained, where work has been done to construct a scheme that includes two solutions as shown in Figure 10. The first one results in the distribution of contact pressures and the second one is the temperature distribution field. The two solutions are coupled with the basic fact that the contact pressure and the frictional heat flow depend on each other for both models. In the thermal model, the pressure is a fundamental step, as is the case in the mechanical model, where the frictional heat is the basis for finding the pressure. The pressures and slip speed were assumed constant over small time periods to obtain a more accurate solution. It has been proved that

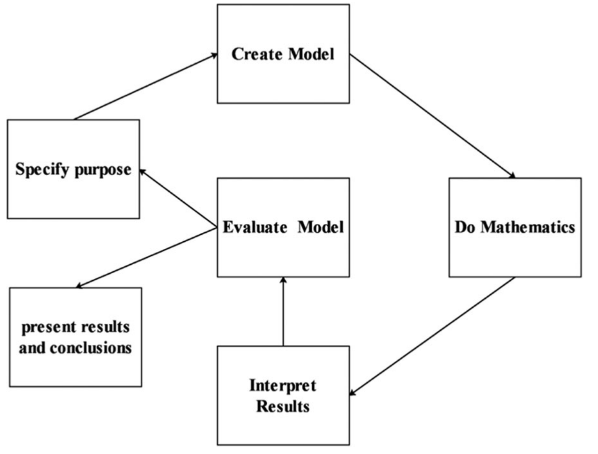

FIGURE 9 Process of mathematical solution[37]

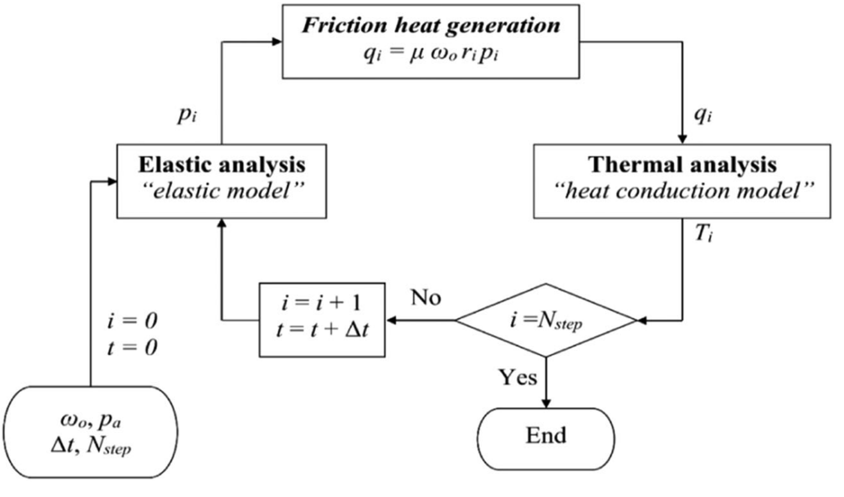

FIGURE 10 Flowchart of sequentially coupled thermal–mechanical approach using finite element method[39]

this solution is a valuable tool for assessing the thermal behavior and the amount of heat flux generated due to friction and distribution of contact pressures.

The analytical solutions for determining the distribution and amount of heat generated between the friction clutch's contact surfaces were improved by Abdullah et al.[1,40,41]

The efforts exerted also focused on determining the correction factor for the equation that governs the heat generated between the rotating parts, as the equation reached gave a reliable rate of the generated energy, including acceptable error values. The results showed the significant effect of neglecting the difference in heat flow with radius on the temperature distribution as well as the maximum temperature.

Pica[42] proposed new models of torque of the dry clutch system that include the effect of temperature and slipping speed. Two thermal models were built and linked by torque to complete the engagement of the system based on the experimental data from the automobile manufacturers. The results showed the effects of temperature and slip speed on torque. The real-time simulation findings showed that if the temperature increase is not accounted for properly, the dry clutch's performance may worsen. The results of the new model were proved to estimate the temperatures to be compensated instead of the missing values in the torque characteristic. This study presented the first step, studying and analyzing the possibility of integrating torque with a disturbance observer.

Gkinis et al.[24] presented the thermal analysis based mainly on the law of energy conservation between losses due to friction and heat generated to assemble the dry clutch components. The work aimed to measure the properties of the new and worn friction lining, as well as to use a new approach to study the combined effect of a number of variables: microstructure, thermal properties, heat generation mechanisms, lining wear effect, and mainly heat transfer. The results showed that the thermal energy loss is less due to the higher friction coefficient compared to the worn lining.

Al-Shabibi[43] studied the problem of thermoelastic instability in the case of high slip speed, which explains the coupling between the heat equation and thermoelastic. The study tended to investigate the issue of instability and thermoelasticity to follow two distinct approaches, namely the analytical approach and the approach that relies on finite elements. The first one deals with simplified shapes, while the second one fits more with the more complex form. The methods used in the analysis will assist in the identification of developed transient problem areas, such as the evolution of contact pressure and temperature over time. It also provides assistance in material production by means of calculating thermal stresses and finally assessing the design criterion.

Sherza et al.[44,45] applied analytical and numerical solutions to determine the two-stage clutch disc transient thermal response. The first stage includes identifying the system during the sliding period, such as the amount of heat produced and the distribution of the heat produced in both hypotheses, whether of uniform wear or uniform pressure. The results showed that the maximum temperature values for uniform pressure conditions are greater than those for uniform wear conditions, and this explains why the design engineers were inclined to the second hypothesis. The temperature and heat generated for each clutch component (pressure plate, clutch disc, and flywheel) were estimated using the thermal partition ratio. The other stage worked on provided an analytical solution to calculate the heat generated between the clutch parts based on the assumption of uniform pressure only under various working conditions, such as torque, slip speed, and so on. The results indicated that the largest temperature was in the middle of the slide period and its maximum value occurred at the outer radius.

Bhandari and Mane[46] studied the behavior of thermal buckling of the automotive clutch disc. Thermal buckling rarely occurs at the beginning of clutch engagement due to the fact that it appears after the temperature reaches the critical state. The finite element method was used to analyze the thermal buckling problem and calculate the critical bending temperature. The results were compared with a precise analytical solution because the thermal buckling is greatly affected by the thermal properties of the material. The automotive engineers recommended, including the effect of thermal properties of the material in the design process. Yu et al.[18] presented numerical simulation as an experimental validation of the thermal model to analyze the surface temperature changes between different friction pairs. The numerical solution is used to verify the temperature distribution between the different pairs, while the experimental solution is used to evaluate the accuracy of the theoretical solution. It was concluded based on the results that there is a large temperature gradient at the axis while along the axial direction and for the individual pair the friction torque was decreased.

Chen and Liu[10] presented a solution to the cylindrically shaped contact problems, which is characterized by the continuity of the harmonic sliding state on a semi-final level in the presence of frictional heating. The method of solving the paired equation relied on the method of functional organization, which proved to be highly effective. Two directions were used to simplify the issue, which is the case of the steady-state, in addition to the stress of the plane, as the study did not address the transient state and the state of rotation with slipping. The introduction of the effect of time and the state of rotational slip was then taken care of in many research, for example, Awrejcewicz and Grzelczyk[47] studied the processes of heat generation and diffusion in a dry clutch by developing a mathematical model, which focused on the uneven distribution of heat produced in a mechanical clutch, the thermal conductivity between the friction lining materials, and the heat transfer between the friction lining to the environment. The mathematical solution included a complete description by means of a set of homogeneous and heterogeneous linear equations. It was used as an algorithm analysis for a nondimensional solution and finally used in the numerical solution. The theoretical results were very much in agreement with the experimental results, which confirmed the accuracy and effectiveness of numerical analysis. It was recommended to apply, including more variables than are used in this study. On the numerical level, Kılıç et al.[21] used computational fluid dynamics to build a 3D model of the transient state in the dry clutch, to investigate the temperature distribution after reducing the weight provided that the ability of the clutch to dissipate heat is not affected. The used technique succeeded in being a key to further improvement in the design of the system. The simulation results showed that the heating time of the parts is shorter than the cooling time, and on the other hand, the maximum temperature and heat dissipation rate is greatly affected by the compression values of the pressure plate.

6 | EFFECTIVE PARAMETERS ON THE THERMAL BEHAVIOR OF CLUTCH SYSTEMS

A dry clutch, in particular, is subject to a range of working conditions, such as spinning, slipping, and friction in the dry state, resulting in parameters, such as speed, friction material, number of engagements, face thickness, and roughness being visible. All of these factors greatly affect the performance and life of the clutch through their influence on the amount and distribution of the heat generated by friction (in other words, thermal and thermoelastic behavior). Research interest in these factors and any attempt to study them extensively, and to identify the effective limits and extents that achieve the best working conditions are the main concern of design engineers and manufacturers. Hence, this section of the paper chronicles the last of the research that focused on this topic especially and distinctively.

6.1 | Sliding speed

The sliding speed greatly affects the temperature and thermal stress in all sliding systems, such as the clutch and brakes, where it can change the status of the clutch system from stable to unstable under certain working conditions.[48]

Abdullah et al.[48] researched the effect of slip speed on thermal stresses in a single clutch disc by developing a numerical approach based mainly on the finite element method. The approach combined the elastic analysis with transient thermal analysis to calculate the temperature distribution during the sliding phase at any time. The results showed an important discovery that the value of the slip speed greatly affects the stability of the system, and on the other hand, a large increase in the value of thermal stresses occurred due to the sliding speed exceeding a critical threshold. Al-Zubaidi et al.[49] worked to reach the safe working area of the sliding system to avoid failure in the contacting surfaces of dry friction clutch systems. Also, they investigated the effect of slip speed on the friction behavior and temperature range of a ceramic clutch pad. Numerous experimental tests showed the clear effect of temperature on the coefficient of friction, although the ceramic materials provided a thermally stable performance well. The slipping speed had a great influence on the coefficient of friction and the temperature. Finally, it was recommended to avoid failure, the friction clutch system should be kept under the critical speed. Figures 11 and 12 illustrate the effect of increasing the slipping speed on the coefficient of friction and the values of wear experimentally, where the experimental results show that the rate of wear increased with the increase in the speed of the slip because the rate of wear is closely related to the properties of the friction material such as the thermal conductivity, as it led to a decrease in the coefficient of friction and an increase in the rate of surface temperatures. Hence, an increase in the rate of material removal and thus the formation of the rough surface.[50] For dry dual clutches, a transmitted torque model has been developed by Pica.[42] The model, whose parameters were fine-tuned using specific studies and real-world data from the automobile industry, demonstrates how temperature and slip speed affect clutch torque transmission. Real-time simulation findings generated using detailed software in the loop model reveal that if the temperature increase is not corrected, major degradations in clutch engagement performance can occur. The proposed compensations for the dependencies of clutch torque on temperature and slip speed are effective, as shown by the closed-loop results. While, Sherza et al.[45] worked on improving the analytical solution based on

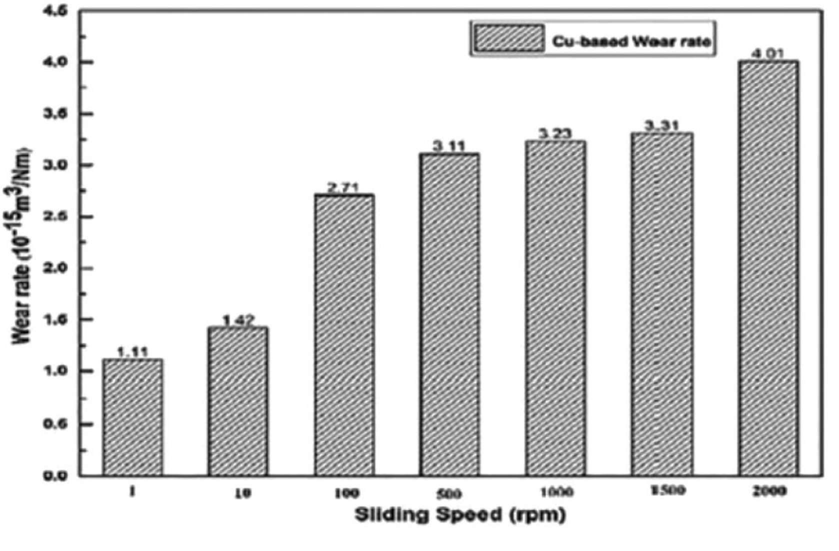

FIGURE 11 Experiential results of varying the slip speed with wear rate[50]

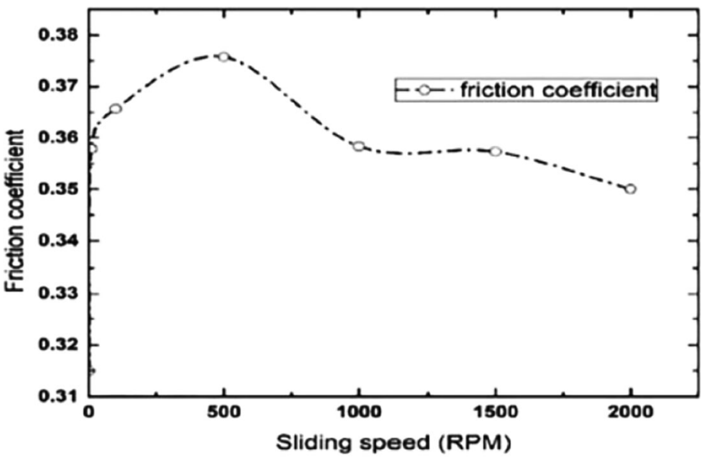

FIGURE 12 Experiential results of varying the slip speed with friction coefficient[50]

the equations of motion (two-inertia system) to compute the frictional heat created between the friction clutch's contact surfaces under various working conditions, such as torque, sliding speed, and so on. A consistent pressure was expected over the friction clutch disc's surface.

6.2 | Friction material

In the last decades, there have been many studies about the development of tribological systems and reducing the magnitude of wear and friction to the minimum level based on new solutions to the tribological problems. The increasing temperature occurs due to the frictional heat generation, which will be the result of the sliding process between the two surfaces that are in contact. Heat deformations that result from the generated heat eventually lead to thermal cracks and deformations that are responsible for the failure of the friction material before the end of its design life. Therefore, the researchers continue investigations to find the most suitable friction materials to improve the performance of the clutch and increase its lifetime.

Faidh-Allah[51] studied the effect of the friction material on the transient thermal behavior of a single-disc dry clutch. A new mathematical solution has been developed that aims to compare the behaviors of clutch systems when using organic and sintered friction disc and during slip periods. The analysis was divided into two models: one of them was concerned with calculating the contact pressures, while the other was concerned with determining the temperature distribution in the system. The numerical solution was based on Galerkin's method for solving mathematical equations and obtaining results of the problem, which showed that the thermal behavior improved by reduction of up to 11% from the maximum temperature if the friction material was made from sintered type instead of organic.

Al-Zubaidi and Abdullah[52] studied experimentally the behavior of frictional materials that are utilized in clutch discs under dry conditions. The results showed that the thermal effect has a significant negative effect on the frictional characteristics, where the magnitudes of the frictional force and coefficient of friction decreased when the surrounding temperature increased. Ali et al.[53] used the transient thermal module to find the general appearance of the temperature distribution in a number of friction materials of the clutch disc. The study compared the harmful conventional material with other compounds consisting of fiberglass S2, carbon–carbon compound, and aluminum matrix composite. The aluminum matrix proved to be the best choice because it provided the highest performance compared to other available materials, where the lowest wear effect appeared, and thus the service life was longer and greatly stable.

Biczó et al.[54] used a new reinforced friction material with woven fiber yarns that are specifically: fiberglass with copper and aromatic polyamide material and friction material reinforced with acrylic nitrile. The purpose of using such material is to study the mechanical and thermal properties of the new hybrid material and the possibility of its use in dry friction clutches. They developed a thermomechanical model that contributed effectively to characterizing hybrid friction materials. In this study, it was considered a valuable reference to give the necessary guidance when working in this direction. The values of the coefficient of friction were affected by the temperature,where this variation had different behavior from one material to another based on the physical properties. Figure 13 shows the relationship of woven materials where it is possible to identify the effect of the increased temperature on the coefficient of friction. They increase the temperature and then the effect begins to take a turn. Unfortunately, the maximum temperature that can be within the service range of such materials is 250°C. Figure 14 illustrates the acceptable materials that enter the industry, as these materials are characterized by a more stable rate in relation to the coefficient of friction with the continuous increase of temperature during work. Figure 15 depicted an experimental comparison of the thermal and frictional properties of the new and worn lining materials (i.e., after a distance of 50,000 km), as it demonstrated that the temperature of the new material is higher than the worn because the latter has a higher coefficient of friction, which means a higher rate of heat generation, and also that the temperature increased with increasing time. The studied friction materials varied remarkably to try to reach the best thermal behavior of the clutch lining, for example, Ramesh et al.[55] used different materials (VH-03, G95, SF-CPX61, and SF-MC2), Koranteng et al.[50] relied on a Cu-based composite, Bhaduri and MuruguNachippan[35] worked on comparing several materials (molded asbestos, sintered iron, Al-MMC F3D20S-T5, Al-MMC F3S20S-T61), while fiber-reinforced hybrid composites have been studied by Biczó et al.,[54] Bhandari and Mane[46] focused on aluminum alloy (A-360), and Harish and Kumar[56] compared three materials (asbestos, Kevlar 29, sintered iron).

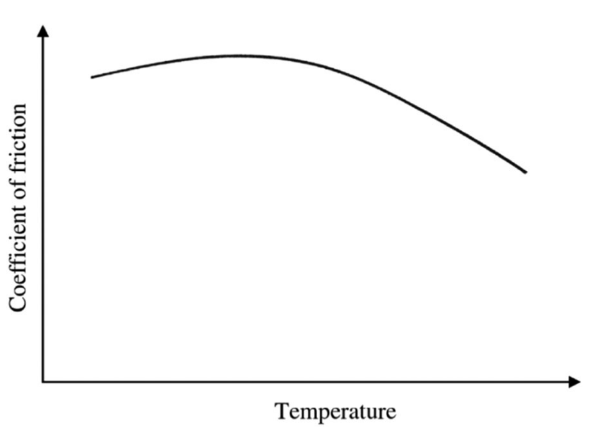

FIGURE 13 Typical curve of friction/temperature of a good quality woven material[55]

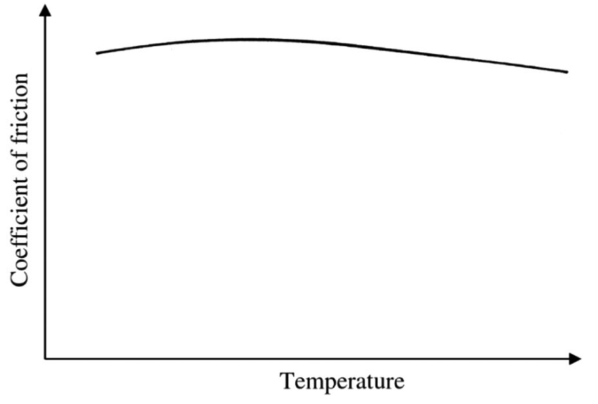

FIGURE 14 Typical curve of friction/temperature of a good quality molded material[55]

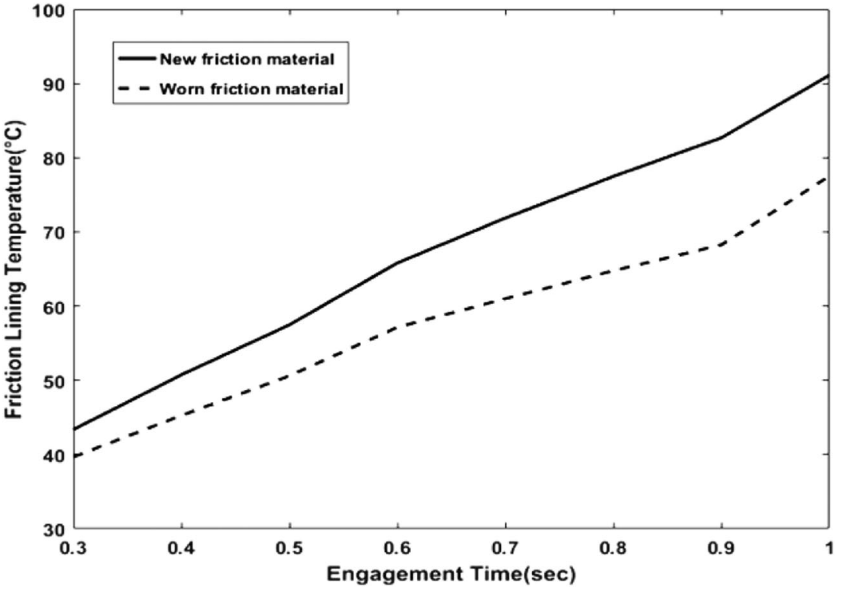

FIGURE 15 The experimental comparison of the thermal behavior between new and worn friction materials during the engagement period in the dry clutch[43]

6.3 | Repeated engagements

The importance of studying the repeated engagements (multiple engagements) of the friction clutch system is due to the quick increasing of the surface temperature in each new engagement until reaching the maximum value at the last engagement. The level of generated temperature is a function of the number of repeated engagements. The maximum temperatures should not exceed the permissible value based on the selected materials.[57] Many researchers studied the influence of repeated engagements on the thermal behavior of dry friction clutches.[31,58–60] These studies provided some solutions to overcome the thermal problems resulting from repeated engagements. Finite element models were developed to fully analyze the thermal matter and aid in predicting the surface temperature and the number of permissible engagements according to the working conditions. The results found that in all the engagements, the critical time occurs near the middle of the slip period, where the maximum temperatures occur.

Abdullah et al.[25] studied the extent to which the temperature values and their distribution (thermal behavior) were affected by the increase in the number of engagements based on the hypothesis of uniform pressure between surfaces in a dry clutch. The numerical simulations were conducted to analyze the thermal problem of the clutch based on four repeated engagements during the sliding period. A 3D model was built to find the numerical results. Figure 16 shows the behavior of surface temperatures during the number of repeated engagements. Although the temperature generally increased in the regions of the outer radius, it decreased in the areas close to the inner radius. A sharp decreasing in the temperature can be seen in the area of the grooves, which is happened due to effect of convection in these areas. Figure 17 illustrates the variation of maximum surface temperatures at different thicknesses of frictional facing during six engagements. It showed that the temperatures decreased dramatically deeper in the thickness of the frictional facing due to the poor thermal properties of the friction material.

6.4 | Facing thickness

The frictional facing material thickness is a very important variable affecting the thermal behavior and elasticity of a dry friction clutch, and it has been investigated through several studies.[61,62] Several new finite element models were introduced to analyze the thermal and thermoelastic problems based on numerical simulation. The results proved that the frictional facing thickness is inversely proportional to the contact pressure, and its effect is directly proportional to the thermal deformation over the length of the slip period. Therefore, the frictional facing thickness is considered an important factor in conjunction with other parameters, such as permissible pressure, maximum slip speed, and transport capacity. Figure 18 shows the maximum surface temperature of a clutch disc over the heating period using different values of the frictional facing (1, 2, and 3 mm). When the frictional facing thickness is 1 mm, the highest temperature will be generated, and when the frictional facing thickness is 3 mm, the lowest temperatures occur. Up to 0.24 s, the temperature differences increased between cases of the thickness of 1 mm and cases of the thickness of 3 mm. Later on, the differences begin to decrease gradually. It was concluded that if the thickness of the interface is thin, the thermal deformation will greatly affect the contact pressures, and then the temperature will increase (the heat generated) and the contact area will decrease too. This occurred due to the increase in pressure in the specific areas within the contact area. A decrease in the temperature of the contact surfaces, and thus the heat deformations, have a lesser influence on the contact pressures because they are more uniform in terms of the distribution on the surfaces.

6.5 | Surface roughness

The contact area is distributed into a number of microscopic contact areas. Therefore, the real contact surfaces are rough and not flat, as assumed by a number of researchers when applying the numerical approach to find the solution to contact problems for a clutch. This fact will have

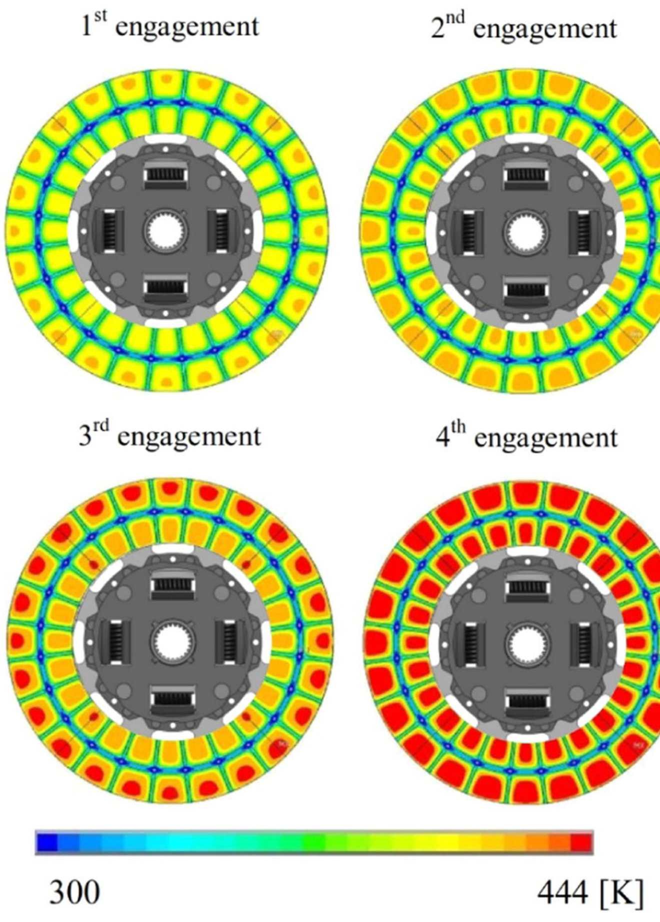

FIGURE 16 Temperature distribution of friction clutch disc during engagements[25]

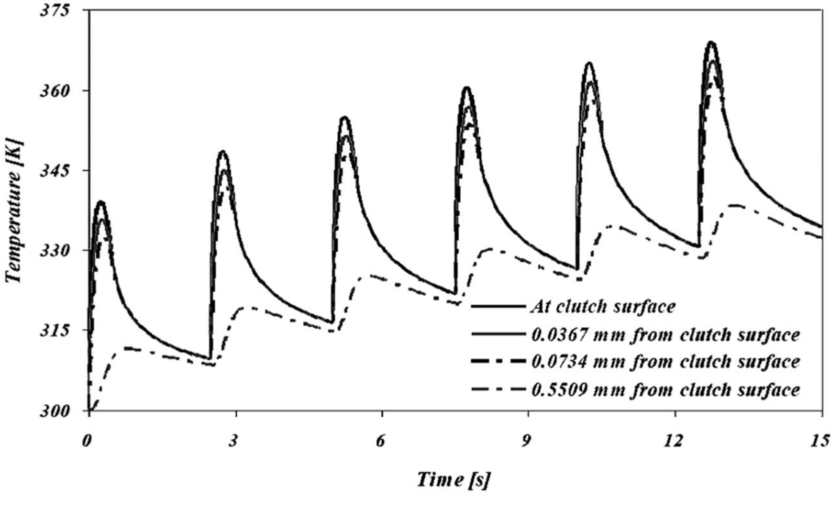

FIGURE 17 The maximum surface temperature through six successive engagements[51]

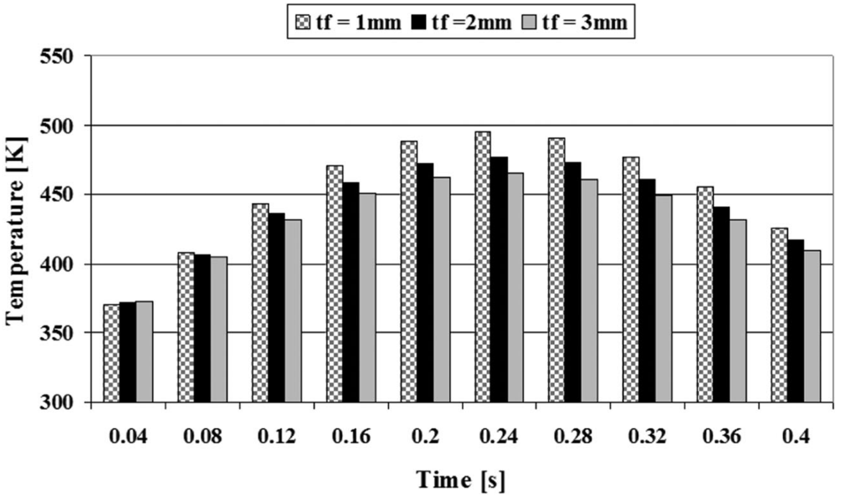

FIGURE 18 Maximum surface temperature of the friction clutch disc with different frictional facing thicknesses[48]

a significant impact on the effectiveness and performance of the sliding system, as well as the contact phenomenon in general.

Mostly, it is assumed in solutions that the surface is divided into a group of subareas of the impact of the loads. Therefore, the total load is equal to the sum of the individual loads that compress each of them over a certain distance, depending on initial surface conditions.

Abdullah et al.[6] investigated the effect of roughness of surfaces on the friction clutch disc on the thermoelastic behavior of the friction clutch. The results showed numerical results based on the real surface roughness that was measured experimentally. A new model for finite elements was developed over the period of slip to simulate the thermomechanical problem. The results presented a set of important facts, such as at the beginning of the engagement, the pressures will focus on very small zones that are on the top of the rough contact surfaces. But with the passage of time, the actual contact area will increase as a result of an increase in the rate of wear, causing a failure in the friction material. Also, the results confirmed the harmonious relationship between the upper values of the generated heat with the higher values of the contact pressures. The maximum value of the temperature will occur at the highest points (peaks), while the minimum value of the temperature will be located in the lowest groove on the surface. This explains the thermal behavior when comparing the flat surface to the rough surface as shown in Figure 19, which shows the relationship between the surface roughness and the temperature distribution on flat and rough surfaces.

7 | CONCLUSIONS

In this review paper, the most important literature that relates to the subject of thermal and thermoelastic analyses for friction clutch systems was reviewed. The solutions provided by researchers in this field have varied, where most of them resorted to numerical solutions, and others apply experimental solutions, while a very limited number of researchers enhanced the analytical solutions.

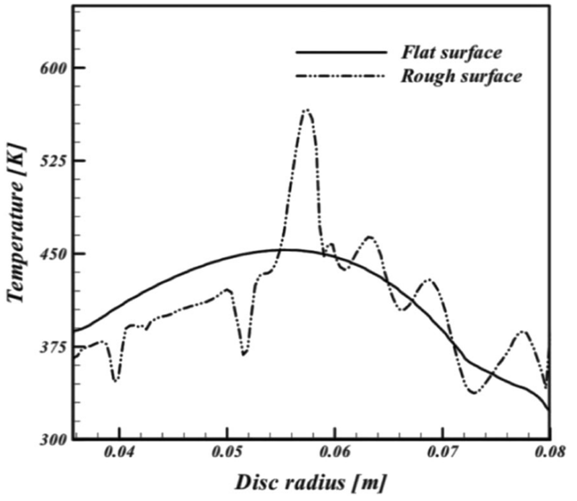

FIGURE 19 The surface temperature variation is relative to disc radius in a single-disc clutch (pressure plate side, $t = 0.25\, t_s$)[6]

The most important conclusions that were reached after this wide and deep research are as follows:

1. The majority of researchers focused on numerical solutions more than experimental work, where the experimental work requires large costs and also a long period of time to build the suitable test rig to obtain reliable results. The main reason for researchers to adopt the numerical solution (e.g., finite element method) to find the thermal and thermoelastic solution for the friction clutch is to obtain acceptable results at a low cost. Numerical results can be utilized in the industrial sector for design purposes and manufacturing. Also, the great variety of numerical software that is currently available with the existence of very fast computers, in addition to the availability of input data for materials and dimensions that are required.
2. A very limited amount of research provided analytical solutions to the thermal problem of the friction clutch due to the complexity of the geometry and the existence of many variables (sliding speed, friction characteristics, function of applied pressure, status of contact surfaces, material properties, degree of air cooling for the system, dimensions, etc.) that interact together. This leads to difficulty neglecting these variables to obtain the behavior of the clutch system under different working conditions, in addition to not converging the analytical solution in most cases of the thermoelastic problem.
3. The results showed that the frictional facing thickness has a significant effect on the distribution of the frictional heat generated, contact pressure, and temperature. Also, the actual contact area between the contacting parts was influential as well. When reducing the thickness of the frictional facing (less than the critical thickness), the status of the system will change from stable to unstable. This will focus the contact pressure on small zones of the nominal contact area that lead to a dramatic increase in the heat generated and, finally, the surface temperatures grow quickly and may exceed the allowable temperature in some cases.
4. It was found that the function of the applied pressure is one of the effective design factors of the friction clutch, where when applying a step function (slipping time is very short), the

surface temperature will be at the highest level. On the other hand, when applying the pressure as linear increases with time (slipping time is equal to double the slipping time of step function), in this case, the surface temperature will be at the lowest level.

5. It was found that repeated engagements have a great influence on the thermal behavior of the clutch system, where the system temperature will be increased very quickly with each new engagement to reach the peak at the last engagement. Based on the available literature, it was found that only a few researchers covered this point and its need for deep theoretical and experimental study to understand the thermal and thermoelastic behavior of the clutch system under this working condition.
6. One of the main factors that greatly affect the thermal behavior, performance, and life of a friction clutch system is the thermal properties of the friction and steel materials used. For example, if the conductivity value of steel parts (pressure plate and flywheel) decreased by 15% of its original value,[36,63] the temperature is increased by 8°C in one engagement. This increment in the temperature will be increased more and more with each new engagement in the case of repeated engagements, and in such cases will lead to premature failure of the contacting surfaces.
7. The research that was extrapolated was not concerned with analyzing the dependent materials (when the friction and steel materials are a function of temperature and position) on the distributions of the contact and temperature of the contacting surfaces (friction clutch, flywheel, and pressure plate). Also, the effect of the dependent materials on the thermal stresses of the system.
8. In the last 10 years, not much research has been published—especially on the experimental side—concerned with the effect of some important factors on the performance of the dry clutch, such as surface roughness, face thickness, and so on. The reason for this may be the development of numerical methods and simulation programs that provide freer space and more flexible methods of analyzing dry clutch problems.

8 | SUGGESTIONS FOR FURTHER FUTURE WORK

1. Study the effect of gap conductance. The results of the transient simulations have been obtained assuming perfect thermal conductance at the interface.
2. The transient analysis discussed assumed that there is no wear included in the problem. However, the wear effect is a significant variable for automotive clutches. There should be coupled the interaction among all of the contact pressure, temperature, and wear. Therefore, a new mathematical model should be developed to find the solution to the thermoelastic problem, including the wear during the engagement.
3. Find mathematically the relation between the energy dissipated during the sliding period of the friction clutch system and the wear rate at any instant during the engagement process.
4. Develop a new numerical model of the thermoelastic transient problem that takes all complexities of geometry, where the effect of nonuniform load can be investigated on the behavior and performance of the clutch system.
5. Researchers and the industrial sector should consider the importance of experimental results combined with theoretical results. This aspect will lead to obtaining an accurate evaluation of the performance of friction clutch systems under different working conditions, in addition to the possibility of studying the development and improvement of the system.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in ScienceDirect at https://www.sciencedirect.com/science/article/pii/S2214157X17303039.

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