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RESIDUAL STRESS-INDUCED DAMAGE IN BRAKE DRUMS

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1. Introduction

The braking system represents one of the vital subsystems of the complex mechanical system of a motor vehicle. Together with the steering system and the tires, it plays a decisive role in the active safety of motor vehicles and road users [1]. Brakes, as the actuators of individual subsystems, have a particularly important role in considerations of the reliability of motor vehicle braking systems due to their operating conditions and their influence on vehicle safety [2]. In motor vehicles, two basic types are used: drum (radial) brakes and disc (axial) brakes. On the rear wheels of heavy vehicles, drum brakes are most commonly applied. Because of their good characteristics, these brakes are also applied on the front wheels of motor vehicles, especially on vehicles with larger mass. Since the rear-wheel brakes also serve as the actuators of the parking (auxiliary) brake, the importance of drum brakes for the reliable and safe operation of motor vehicle braking systems is evident.

Based on the failure modes, effects, and criticality analysis (FMECA) of drum brake components in motor vehicles, it has been determined that the brake linings and the brake drum exhibit the highest criticality [3]. Criticality represents a relative measure of the severity of failure mode consequences and the frequency of their occurrence.

The concept of residual stresses refers to internal stresses that exist in materials and structures independently of any external loads [4]. In metals, particularly in steels, residual stresses may arise due to [5]:

- non-uniform chemical composition,
- unequal plastic deformations during transformations at room or elevated temperatures,
- unequal plastic deformations caused by non-uniform heating or cooling in different zones of the cross-section,
- structural deformations associated with volume changes in the structure, for example during steel hardening processes,
- non-uniform plastic deformations in the cross-section of a machine element induced by service loading at room or elevated temperatures.

With regard to residual stresses in brake drums, it is important to note that brake drums are manufactured from a special type of cast iron, which is thermally conductive and wear-resistant.

2. Failure analysis of drum brakes

In drum brake systems for motor vehicles either complete or partial failures may occur [3]. Complete failures, which are rare, arise when the brake is unable to generate any braking torque. Partial failures, on the other hand, lead to a significant deterioration in the drum brake's operating characteristics, including braking torque, operating temperature, braking uniformity, and the intensity of noise generated during braking.

Failures that lead to a reduction in braking torque are commonly referred to as friction failures. These can be either permanent or transient. Permanent friction failures of a drum brake may result, among other causes, from damage to the drum and the brake shoe linings.

Overheating of drum brake components occurs when the heat generated by converting the vehicle's kinetic energy during motion exceeds the amount of thermal energy that brake components can dissipate to the surroundings. This situation arises during prolonged braking on downhill descents, frequent use of the brakes, or incomplete brake release when the brake is not actively engaged. Sustained high operating temperatures of drum brake parts can lead to thermal overloading and burning of the brake shoe lining material. In addition, overheating of drum brake components may cause: deformation of elements (drum ovality, shoe distortion), drum cracking, the occurrence of blue spots and martensitic patches on the drum friction surface, brake lining damage, changes in material properties (e.g., loss of elasticity of return springs), accelerated aging of brake cylinder sealing elements, etc.

The most common types of damage to the brake drum of motor vehicle braking systems occurring during operation are [6]: cracked drum, cracks caused by overheating, contamination of the friction surface with grease, occurrence of martensitic spots, deep grooves on the sliding surface, blue discoloration of the sliding surface, polished surface, drum deformation, excessive wear, thinning of the drum, circumferential cracking of the drum's mounting ring and radial cracking of the mounting ring at the bolt holes. The subsequent sections present a detailed analysis of brake drum failures resulting from residual stresses induced by operational regimes and service conditions during use.

3. Thermal cracks

Heat-checking or thermal cracks appear as a series of narrow, short, and shallow cracks on the braking surface of the drum (Fig. 1) [6]. They occur under normal operating conditions due to alternating heating and cooling of the friction surface of the drum and are considered a typical characteristic of drum brakes. These cracks do not affect braking torque or other functional parameters. Because of their shallow depth, thermal cracks usually wear away during operation as the friction surface of the drum undergoes normal wear, but they reappear again as a result of the braking process. However, there is a possibility that over time heat-checking may develop into more serious cracks, which would require drum replacement. Therefore, during routine inspections of a vehicle's braking system, special attention should also be paid to the condition of thermal cracks on the drum.

Fig. 1. Heat-checking.

As shown in Fig. 1, thermal cracks appear on the friction surface of the drum that is closer to the mounting plate. On the opposite side, where the drum is cooled more evenly, such cracks are almost absent. All thermal cracks are oriented in the axial direction of the drum. This indicates that they occur as a result of tangential tensile stresses on the friction surface that arise during the cooling of the drum. How can the formation of thermal cracks be explained?

During braking, intensive local heating of the contact surfaces between the drum and the brake linings occurs. As the temperature rises, the diameter of the material layers near the friction surface of the drum increases. This expansion is constrained by the adjacent layers of material that are less heated. Consequently, the outer layers of the drum wall are subjected to tensile stresses, while the inner layers are subjected to compressive stresses. If the total stresses in the outer layers exceed the yield strength, plastic deformation and an increase in drum diameter will occur. When the friction surface cools, its diameter decreases. This contraction is resisted by the plastically deformed outer shell. As a final result of the non-uniform heating and cooling of the drum wall, compressive residual stresses are formed in the plastically deformed outer layers of the drum wall, while tensile tangential residual stresses occur in the interior. It can be assumed that the maximum values of tensile tangential stresses appear in the surface layers of the friction surface. Their intensity is evidently greater than the tensile strength of the drum material, which leads to crack formation.

4. Cracked drum

The most common cause of cracking in brake drums is residual thermal stress, which develops due to uneven heating and cooling during operation. In some cases, the intensity of residual stresses alone may be sufficient to initiate a crack. More frequently, residual stresses are superimposed with service stresses caused by external loads. If the total stress exceeds the tensile strength of the material, a crack will occur, its size being proportional to the stress intensity. Even small cracks in the drum wall can, over time and under dynamic loading, lead to complete drum failure. This raises the question of establishing a criterion for when the brake drum should be replaced, depending on the crack dimensions.

A cracked drum (Fig. 2.) [6] can be detected through visual inspection. The crack typically runs in the axial direction and extends through the entire wall of the drum. It always appears perpendicular to the sliding direction of the brake shoe.

Fig. 2. Cracked drum.

The reduction of drum wall thickness, either due to wear or due to machining aimed at eliminating detected defects, additionally decreases the static strength of the drum and increases the likelihood of crack formation. In the drum section where a crack has developed, elastic deformations are more pronounced, which leads to an uneven pressure distribution along the arc length of the friction lining and to a significant reduction of the braking torque. As a consequence, brake vibrations become strongly pronounced. Depending on the cause of origin, cracks in the drum may occur during the entire service life of the component. A cracked drum must be replaced, which means that this type of failure leads to the complete failure of the brake drum.

5. Brake drum deformation

As with cracked drums, the most common cause of brake drum deformation is residual thermal stress resulting from uneven heating and cooling of the drum during operation. Residual stresses are superimposed with service stresses. If the total stress exceeds the yield strength of the drum material, permanent plastic deformations occur, leading to a loss of concentricity of the friction surface. The circular shape of the friction surface transforms into an oval.

It is important to note that possible causes of drum ovality may also include improper storage of the drum, incorrect tightening during installation, or dropping the drum onto a hard surface during routine vehicle maintenance. In all these cases, residual stresses arise due to uneven plastic deformations at room temperature. However, the decisive factor for further use of the drum is the magnitude of the resulting deformation.

Variation in drum diameter at different points along the braking surface, as well as uneven wear of the drum and brake linings, are indicators of an out-of-round drum. The magnitude of drum deformation is determined by measuring the drum diameter (Fig. 3) [6] at different points on the braking surface.

Fig. 3. Measurement of drum deformations.

On each brake drum, the manufacturer marks the values of the internal diameter of a new drum and the maximum permissible diameter, beyond which mandatory replacement is required. If the maximum measured diameter of the drum's friction surface is smaller than the maximum permissible diameter, the drum can be machined in order to restore concentricity. Otherwise, the drum must be replaced. This means that deformed drums belong to the group of conditionally repairable components.

6. Martensite spots

Martensite spots appear as extremely hard, slightly raised dark patches on the friction surface of the brake drum (Fig. 4) [6]. The presence of these dark spots indicates that the drum has been exposed to operating temperature regimes that caused structural changes in the drum material. During rapid cooling of a heated drum made of gray cast iron, the austenitic structure of the material, with a face-centered cubic lattice, transforms into a martensitic structure with a body-centered cubic lattice. The structural transformation of austenite into martensite results in a relative increase in the material volume, which leads to the formation of raised dark spots on the drum's friction surface.

Fig. 4. Martensite spots.

Due to structural changes in the material, compressive residual stresses occur in the martensitic zones, leading to an increase in material hardness. The color change of the drum material with a martensitic structure can be explained by the presence of graphite in the material structure. Namely, during rapid cooling of gray cast iron, carbon atoms do not have time to diffuse out of the austenite crystals, but remain in the material in the form of graphite needles or flakes.

In general, during the cooling process of steel or gray cast iron, structural stresses arise at the moment of transformation from austenite to martensite due to a significant increase in specific volume. Since martensitic transformation takes place at a temperature at which the material is no longer plastic, residual stresses form immediately. The surface layers of the material with a martensitic structure, due to the volume increase, tend to separate from the austenitic core. As a result, compressive stresses develop in the surface layer, while tensile stresses appear in the core (Fig. 5a) [5]. With further cooling of the material, martensitic transformation continues in the deeper layers. Consequently, the initial stress distribution changes so that the maximum compressive stress shifts from the surface toward the interior, as shown in Fig. 5b).

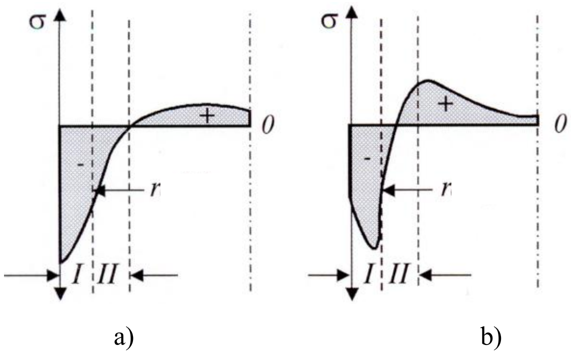

Fig. 5. Schematic of structural stress formation in Cooling Zones I and II: a) onset of martensitic transformation, b) completion of transformation.

The presence of raised, hard, dark spots on the friction surface of the brake drum reduces the effective contact area between the drum and the brake linings. This in turn leads to a decrease in braking torque, severe local heating, uneven wear of the brake linings, brake pedal pulsation, and the occurrence of vibrations and excessive noise during braking. In addition to structural residual stresses, intense local heating and non-uniform cooling of the friction surface give rise to thermal residual stresses. The complex stress state resulting from the combined effect of residual and service stresses causes deformation of the brake drum and the initiation of fatigue cracks on the friction surface. Failure to detect martensitic spots in a timely manner and eliminate the cause of brake drum overheating inevitably leads to mandatory drum replacement.

7. Conclusions

Residual stresses have a significant influence on the service properties and operational life of machine elements. Therefore, it is important during the design phase of machine structures to devote appropriate attention to the causes and consequences of residual stresses.

Residual stresses formed during manufacturing or during service of the brake drum are superimposed with stresses caused by external loading. As a result, the stress state within the brake drum is highly complex and often leads to damage in the form of cracks and deformations, necessitating replacement.

Timely detection of such damage and the implementation of appropriate corrective measures can enhance the reliability and safety of the motor vehicle braking system. In addition, maintenance costs are significantly reduced.

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