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Fundamentals of ductile cast iron scuffing at the boundary lubrication regime

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ABSTRACT

The friction regime of partially lubricated and highly loaded contact when the oil does not entirely separate the rubbing surfaces and its thickness is comparable to the roughness of the surfaces poses, in some cases, risk of scuffing and catastrophic wear.

The present study, on life prediction of tribological systems from ductile cast iron, steel and brass, is shown by an analysis of the fundamental mechanisms of scuffing. Ductile cast iron according to DIN EN 1563 with nodular graphite standard EN ISO 945 is submitted to systematic tribological tests of scuffing and analysed in the context of quasi-conventional tribometry lubricated with reference and reclaimed naphthenic oils.

The 3D morphologies of the rubbing surfaces are characterised and the fundamental conditions of the scuffing process are investigated. The results are elucidated in order to propose a phenomenological description of the analysed wear process and its invariants. Therefore, the role of solid materials as well as the nature of lubricants is both taken into consideration.

1. Introduction

Most of the sliding parts made of ductile cast iron (DCI) are finished by one of the finishing machining processes based on abrasion, such as grinding, honing, and lapping, belt machining or polishing. These finishes offer smooth surfaces and operation in full film tribological conditions, but also at the boundary lubrication regime. The friction regime of partially lubricated highly loaded contact, when the oil does not entirely separate the rubbing surfaces and its thickness is comparable to the roughness of the surfaces poses, in some cases, risk of scuffing and catastrophic wear. Curiously, there is little knowledge regarding the scuffing process of DCI with nodular graphite, however, a great number of elements are submitted to severe tribological conditions, e.g. as engine cylinder blocks, crankshafts, gearbox, camshafts, and machine-tool bases. The obvious technological issue is the “good tribological behaviour of DCI”, but is catastrophic wear predictable? This is one of the scientific principal reasons of this study.

The generalised tribological use of DCI is constantly increasing due to its excellent rheological properties which depend on the graphite nodule characteristics and matrix microstructure, i.e. high ductility, high strength and low wear, and relatively low production costs. The manufacturing cost of DCI products is a complex combination of raw materials prices, mould expenses, foundry working expenses as well as machining different operations, including the abrasive high added value finishing process. The application of DCI for the fabrication of components such as gears, pinions, hydraulic cylinders, crankshafts, brakes, cylinder liners, pistons, and similar parts, which requires improved wear resistance, has drawn much attention to their tribological behaviour in dry as well as lubricated conditions. A non-controlled tribological process can, in some cases, lead to scuffing and therefore to catastrophic wear.

1.1. Tribological specificity of ductile cast iron

In most tribological applications, DCIs play a very specific role due to the very large spectrum of different specific technical and economical characteristics. Its extensive tribological use in ground transport industry, e.g. in trains, tramways, automobiles, tanks, etc., has seen growing scientific interest in the last half-century. In order to optimise cost production, both the machining and casting

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Nomenclature

Abbreviations

DCI	ductile cast iron
HB	Brinell hardness
RDC	relative damping capacity

Parameters

E_{SC} (SE)	scuffing energy [J]
M_T	friction torque [Nm]
n	rotational speed [rpm]
t_{SC}	time to scuffing [s]
t_{SZ}	time to seizure [s]
v	sliding velocity [m/s]

process are today the focus of scientists and engineers. The selection of an optimal friction setting in dry conditions in addition to lubricated conditions of DCI requires high metallurgical knowledge in cooperation with that of experts of tribology, chemistry and rheology, which is not very common and which the authors tried to achieve in this study. DCI is a structurally heterogeneous material due to its composition and, therefore, its tribological behaviour; rheological superficial and volumetric characteristics are strongly influenced by its composition and cooling process.

It is possible to state that “there is no movement without friction”, thus friction always involves vibrations and, therefore, sonic emission [1]. The relative ability of this material to absorb vibration is evaluated as its damping capacity. Components manufactured from materials with a high damping capacity can reduce noise and also minimise the level of applied mechanical stresses.

Excessive vibration can result in inaccuracy in precision machinery and in excessive wear on gear teeth and bearings. Mating surfaces normally considered in steady contact can be caused to fret by vibration.

The unique high damping capacity of grey cast iron is one of this material's most appropriable property. That is why it is perfectly suitable for machine-tools bases and frames, engine cylinder walls or brake parts. The damping capacity of grey iron is considerably greater than that of other iron-based alloys. This behaviour is connected with the flake graphite structure of grey cast iron (including its specific stress–strain characteristics) and internal friction (attributed with the movements of the dislocations in the graphite phase) [2]. The relative damping capacity (RDC) for grey cast iron with coarse flakes of graphite is 100–500, while for grey cast iron with fine flakes of graphite it is 20–100 [3]. Other grades of cast irons have significantly worse damping properties: malleable cast irons 8–15, nodular cast iron 5–20, and white cast irons 2–4 [3,4]. Metallic materials that are different from cast irons are distinguished by even lower (RDC), e.g. pure iron – 5, eutectoid steel – 4, or aluminium – 0.4 [3].

1.2. Scuffing and catastrophic wear

Scuffing is one of the most dangerous forms of wear which is characterised by a sharp increase in resistance to motion and macroscopic, irreversible damage of machine parts. There is no unequivocal outlook on the scuffing definition, but according to the ASTM G40-12 standard it can be determined as a form of wear occurring in an inadequately-lubricated tribosystem that is characterised by macroscopically observable changes in texture with features related to the direction of relative sliding. It seems to be some sort of paradox that the mechanism of scuffing activation is still weakly recognised while many key friction pairs (e.g. piston rings/cylinders, crankshaft necks/bearing pillows, gearboxes, etc.) are exposed to its occurrence. Apart from this fact, it has generally been accepted that the constituent that is necessary but most often insufficient to scuffing in which the lubricated system occurs is the breakdown of the EHL or boundary film. The problem of precise identification of scuffing initiation follows from the fact that none of the specific theories (e.g. [5–9]) describes this process in a universal way; most of these theories concern concrete material pair and applying friction conditions. Some kind of synthesis in this field was carried out by Bowman and Stachowiak [10], who listed several factors conducive (especially in synergic occurrence) to scuffing initiation:

- plastic deformation of asperities
- contact temperature greater than 150 °C
- high pressure within the contact
- influence of lubricant chemistry
- presence of protective surface film
- effect of surface roughness, texture, and material properties.

All of these factors directly or indirectly (due to interaction with the lubricants, atmosphere and co-elements in the friction pair or treatability and possibility to form desired characteristics of the surface) depend on individual material properties. That is why modern techniques look for new materials whose properties will establish some sort of compromise responding to the multi-branch requirements of tribological systems. Ductile cast irons and austempered cast irons (ADI) have recently appeared as significant engineering materials capable of meeting these kinds of features. Due to their specific combination of high strength, toughness, ductility, machinability and fatigue and wear resistance, they have been used in many industries – also in dependable tribological applications [11–13]. Irrespective of the good mechanical properties of DCI, it is necessary to pay attention to its specific tribological behaviour [14]. During friction of every type of DCI, it is possible to observe a release of graphite. Generally, this is an advantageous effect due to the perfect antifriction properties of graphite, but some information remains unknown concerning its rheological and physical–chemical activity in the interface. A fundamental question thus arises about the influence of graphite on scuffing activation and its course. The answer to this question must be sought in three aspects.

First, we should take into consideration the importance of the form and size of graphite and the matrix in which the graphite is embedded. In some works [15,16], the frontier region between graphite and matrix material has been recognised as the key to scuffing initiation. When graphite nodules were pulled out from the matrix due to friction, the resulting free space in the structure is the most common point in which destruction of the surface may begin. Therefore, the most important seems to be the maintenance of graphite nodules in a matrix. It protects the matrix against the formation of weak links and guarantees systematic proportioning of graphite to the real contact area. The mechanical properties of the matrix are the decisive issue here.

Second, the aspect of the quality of surface finishing has to be considered. This factor is directly connected with the presence of graphite on the machined surface. In the case of low-quality surface finishing, large values of valley volumes can be assumed, which may induce two unfavourable effects. A surface prepared in this way may be deficient in graphite which was released at the stage of processing. As a consequence, the surface is void of the