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Effects of deep cryogenic treatment on the dry sliding wear performance of ferrous alloys

R. Thornton*, T. Slatter, H. Ghadbeigi

The University of Sheffield, United Kingdom

A R T I C L E I N F O

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A B S T R A C T

In this study, the effects of cryogenic processing on the dry sliding wear performance and microstructural features of five common engineering materials were investigated. Significant improvements were found in the wear performance of a pearlitic low carbon steel brake material, as well as AISI A2, D6 & M2 tool steels. Optical and scanning electron microscopy of selected specimens indicated a range of changes due to deep cryogenic treatment including graphite flake degradation and pearlite refinement in cast iron and low carbon steel that was previously unreported in the literature. In tool steels, carbide precipitation and microstructural uniformity reported by other investigators was observed. Macro- and micro-hardness testing revealed no significant changes in any of the materials except for the low carbon steel tested, in which measured improvements were judged to be as a result of the refinement of the pearlite matrix due to deep cryogenic treatment.

1. Introduction

Having previously found that cryogenic treatment appeared to have mixed effects on the sliding wear performance of grey cast iron [1], a broader study to investigate the sliding wear performance of a range of cryogenically treated ferrous alloys was conducted by the authors. These materials (including a low carbon steel and three different tool steels) were selected as they are commonly used in applications where sliding wear is a dominant factor in component life (namely as brake discs and cutting tools) as well as representing a selection of important engineering materials. In addition, this study begins to characterise the microstructural changes that have taken place in these materials, through a combination of optical and scanning electron microscopy, and builds upon the analyses carried out in the previous study on grey cast iron.

1.1. *Cryogenic processing*

Cryogenic processing (alternatively cryogenic treatment or cryotreatment) is a sub-zero heat treatment that affects the entire cross-section of materials and components, with the objective of improving properties such as hardness and wear resistance by causing microstructural changes into different stable or metastable states. By careful control of process parameters such as cooling and heating rates, and the use of a nitrogen atmosphere for cooling as opposed to liquid immersion and quenching, issues such as those identified by previous investigators including thermal shock and embrittlement [2], as well as the build-up of vapour ice which can damage the surface of components, can be avoided [3].

Three classes of sub-zero treatments are regularly reported: cold treatment (273–193 K), shallow cryogenic treatment (193–113 K) and deep cryogenic treatment (113–77 K) which is invariably referred to as DCT [4]. It is the latter that was investigated for this study. In a study employing a Taguchi design of experiments methodology, Darwin et al. [5] determined the order of significance of these process parameters as being soaking temperature, soaking time, cooling rate and tempering temperature, for a high chromium martensitic steel.

While numerous benefits of cryotreatment are reported in the literature, its application is currently limited by a lack of understanding of the fundamental metallurgical mechanisms at work, and the effects of alloying elements, initial phase compositions and therefore past heat treatment histories. As will be discussed, there is also currently a lack of investigations in the literature into the effects of cryotreatment on more 'basic' ferrous alloys such as cast irons and non-alloy or plain carbon steels.

1.2. *State-of-the-art of cryogenic treatment*

Cryogenic treatment has been an active area of research since the earliest work of Barron and Mulhern [6] and the seminal work of Barron [7]. In these initial studies, the potential for the significant improvement (up to 718% in the case of AISI D2 tool

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* Corresponding author. Tel.: +44 114 222 7897.
E-mail address: rob.thornton@sheffield.ac.uk (R. Thornton).

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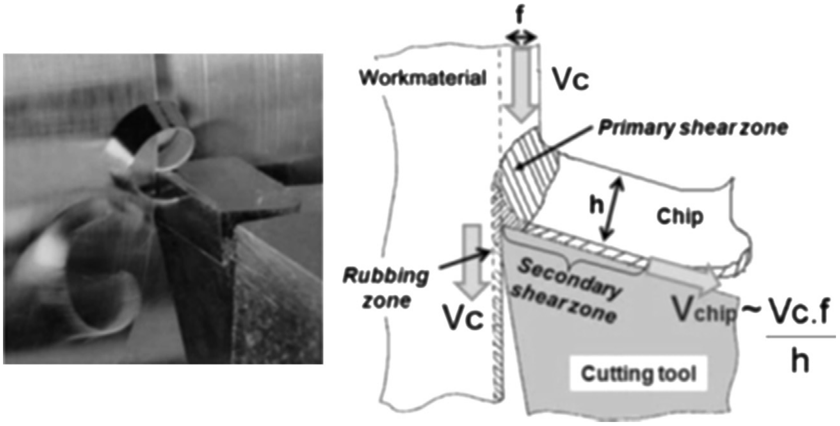

Fig. 1. Standard orthogonal cutting model with different contact zones identified [24].

Table 1
Nominal composition of brake disc materials studied.

%wt	C	Si	Mn	P	S	Cr	Mo	Ni
SAE J431 G10	3.35–3.60	1.90–2.30	0.60–0.90	0.10	0.15	–	–	–
C50R	0.47	0.18	0.75	0.010	0.007	0.03	< 0.01	0.03

Table 2
Nominal composition of tool steels studied.

%wt	C	Si	Mn	Cr	Mo	V	W	P	S
AISI A2	0.95–1.05	0.10–0.40	0.40–0.80	4.80–5.50	0.90–1.20	0.15–0.35	–	0.03 max.	0.03 max.
AISI D6	2.00–2.30	0.10–0.40	0.30–0.60	11.0–13.0	–	–	0.60–0.80	0.03 max.	0.03 max.
AISI M2	0.86–0.94	0.45 max.	0.40 max.	3.80–4.50	4.70–5.20	1.70–2.10	5.90–6.70	0.03 max.	0.03 max.

Table 3
Recent heat treatment histories of tool steels tested.

AISI A2	AISI D6	AISI M2
Heated slowly to 850–870 °C Held for 2 h, lower to 730–750 °C Furnace cooled to 600 °C Removed and air cooled	Heated to 800–840 °C Furnace cooled	Heated to 850 °C Held for 2 h Furnace cooled

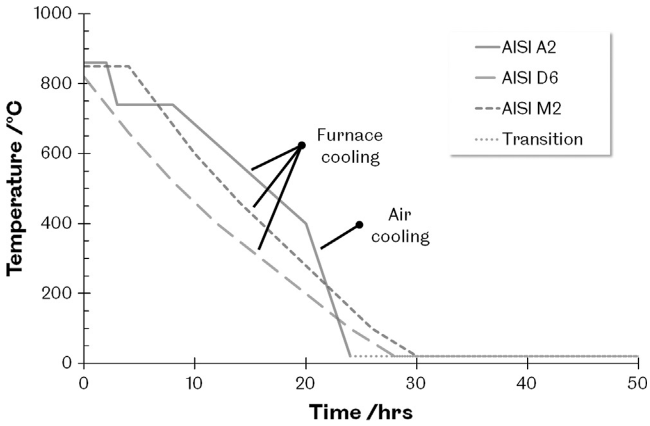

Fig. 2. Recent heat treatment histories of tool steels tested (cooling rates are indicative only) where the 'Transition' line indicates extended time in transit and storage prior to cryotreatment and testing.

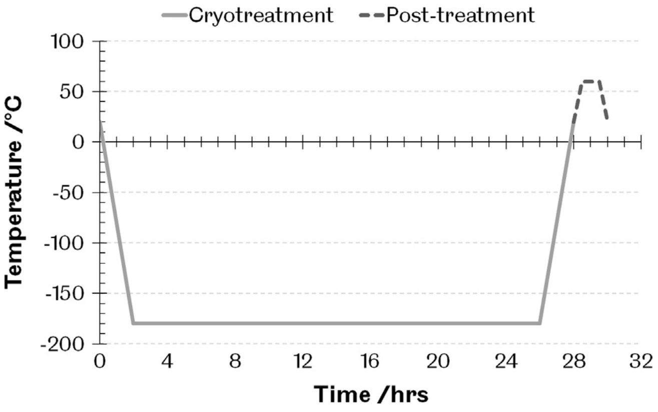

Fig. 3. Deep cryogenic treatment cycle applied to specimens used in this study.

steel) of the abrasive wear resistance of a wide range of ferrous alloys was established, although the microstructural mechanisms responsible, as well as the stability of these changes under varying conditions, was unclear.

The majority of modern studies on the effects of cryogenic treatment have been focused on cutting tool materials. In quench-hardened tool steels numerous authors have confirmed a more complete transformation of austenite to martensite in specimens having undergone both shallow and deep cryogenic treatments [8–11], while increases in the precipitation of small, secondary carbides from tempered martensite have also been observed [12,13]. Less reported is the precipitation of nano-carbides [14]