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Premature thermal fatigue failure of aluminium injection dies with duplex surface treatment

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ABSTRACT

The premature failure of an aluminium injection die with a duplex surface treatment (plasma nitriding and physical vapor deposition coating) was investigated, in an effort to identify the causes of such premature failure of the component. The manufacturing and the operating conditions were documented. Analytical tools were used, including scanning electron microscopy with energy dispersive X-ray capability, X-ray diffraction, and instrumented microhardness testing. Preliminary observations showed a microstructure of coarse tempered martensite, and a considerably rough surface with porosity and cracks. A detailed analysis of crack initiation sites identified sulfur inclusions in the subsurface, underneath the coating. A further revision of the processing conditions revealed that a sulfur-impregnated grinding stone had been used to polish the die. The chemical composition of such grinding stone matched that of the inclusions found in the subsurface of the failed component. Thus, searched causes of premature failure could be discussed on the lights of the present findings.

1. Introduction

Aluminium injection is an efficient and economical process for the manufacturing industry [1], as it combines a number of interesting characteristics: high-speed production, dimensional accuracy, high strength and low weight, simplified assembly, among others. The dies used for aluminium injection processes are subjected to high thermal stresses which, over time lead to failure of the tool by a mechanism of thermal fatigue [2]. Therefore, the tool performance is significantly affected by material properties, manufacturing conditions, heat and thermochemical treatments, or surface coatings.

The materials used for aluminium injection dies are almost invariably hot work steels of the H-type [3]. These steels have traditionally been used in the hardened and tempered condition, which combines tempering resistance and toughness at working temperatures as high as 500 °C. This is a consequence of the precipitation of stable metallic carbides upon tempering. Moreover, the grain size and the shape of carbide precipitates control the mechanical properties of the bulk material.

The effect of manufacturing techniques on material performance is very significant. The surface deformation and the temperature developed during mechanical machining or grinding and electro-discharge machining (EDM) may induce phase transformations and residual stresses [4]. Depending on the type and magnitude, these can have a beneficial or a catastrophic influence on performance. Furthermore, EDM has been reported to severely affect the surface integrity, by producing rough surfaces and high tensile residual stresses [5]. Nevertheless, this technique offers advantages over other manufacturing processes, and is therefore extensively used in production [6].

More recently, plasma thermochemical treatments and surface coatings have been introduced. Although increasing the wear resistance of the tools and extending their service life [7–9], these surface engineering treatments usually have a negative effect on thermal fatigue resistance [10]. Furthermore, the manufacturing processes and surface conditioning have a noticeable influence on the performance of surface engineered dies. The surface integrity, the presence of reaction layers [11] and recasted layers [12] decrease the adhesion of coatings and facilitate the nucleation and propagation of fatigue cracks.

In this work, the premature failure of an aluminium injection die was analyzed. The possible causes of failure such as steel microstructure, heat treatment, manufacturing processing, and surface engineering treatment, namely thermochemical treatment and physical vapor deposition (PVD) coating were assessed.

2. Experimental

A die for aluminium injection was produced with H11 steel, of chemical composition as reported in Table 1. After a standard

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Table 1
Chemical composition of H11 tool steel.

	Element (wt%)								
	C	Si	Mn	P	S	Cr	Mo	Ni	V
Standard	0.330.43	0.801.20	0.200.50			4.755.50	1.101.60	0.3Max	0.300.60
Sample	0.33	0.21	0.25	0.01	0.001	4.96	1.31	0.1	0.39

Table 2
Die manufacturing conditions.

	Tool diameter (mm)	Rotating speed (rpm)	Feeding depth (mm/m)
Rough machining 1	32	1790	6963
Rough machining 2	15	4000	820
Rough machining 3	8	5570	1100
Heat treatment (hardening and double-tempering)			
Fine machining 1	16	6900	1500
Fine machining 2	8	10,900	1390
Fine machining 3	3	12,700	1018
Electro-discharge machining 0.08 mm gap, speed < 4 mm^3/min			
Polishing: grinding stone #150, #220 and grinding paper #180 and #320			
Duplex surface treatment: plasma nitriding and PVD CrN coating			

rough machining operation (Table 2), the part was sent back to the steel maker for appropriate heat treatment, using standard conditions for this type of steel (hardened and double tempered at 600 °C and 560 °C respectively, to a final hardness between 44 and 46 HRC). Subsequently, the part was finely machined, electro-discharge machined (EDM) and ground. The latter process was expected to remove the 'white recasted layer' produced by EDM. Finally, a duplex surface treatment was applied to the tool, consisting of an 80 μm thick plasma nitrided layer with a 2 μm thick CrN PVD coating on top.

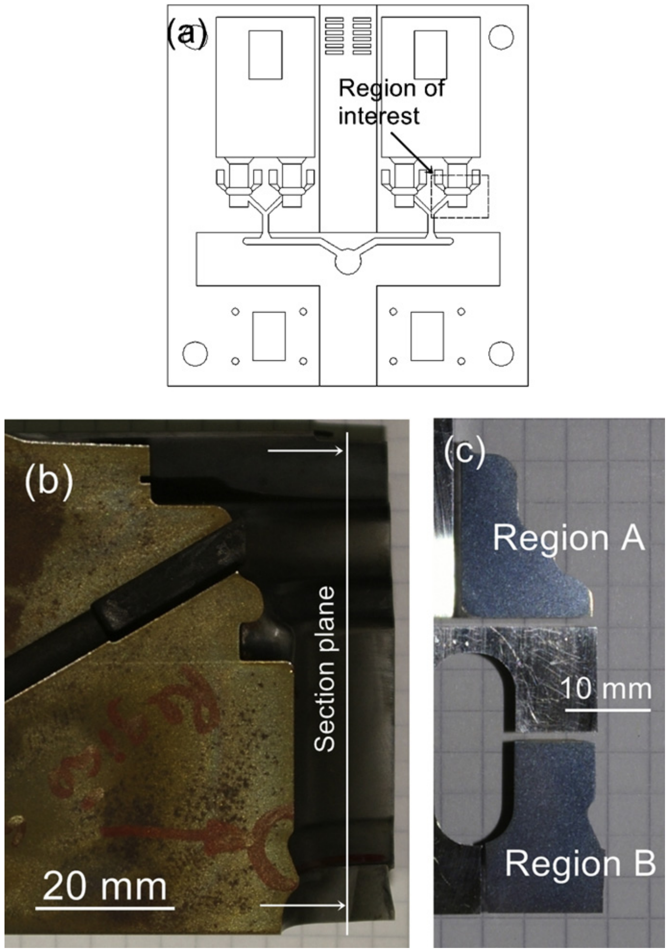

Fig. 1. (a) Schematic of the die and the area of interest; (b) macrograph of the part of the die used in this work; and (c) regions of interest: A and B.

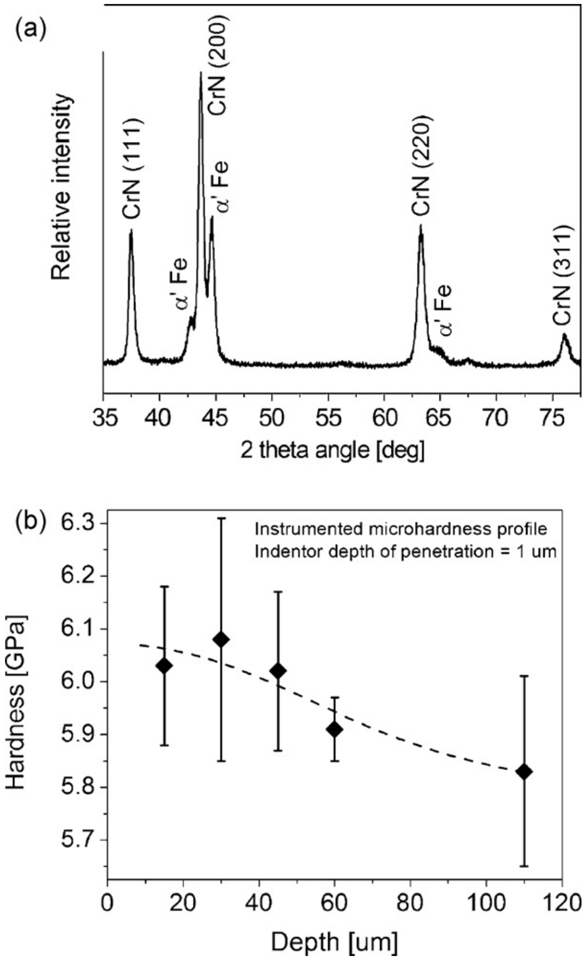

Fig. 2. (a) XRD pattern of the coated steel and (b) hardness profile.