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Residual stresses, distortion and surface roughness produced by grinding thin wall ductile iron plates

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Abstract

This work deals with grinding effects on thin wall ductile iron plates. Residual stresses, shape distortion and surface roughness were measured on thin wall plates of different nodule count, ferritised and afterwards dry ground under several grinding conditions. In all cases, tensile residual stresses are maximum at the surface, and their profile decreases with depth until becoming compressive. No phase transformations can be observed at depths of up to 30 μm below surface, although plastic deformation is visible through nodules and grains enlargement. Distortion increases when the depth of cut and nodule count increase and the workspeed decreases. The mean stresses of the profile tensile zone also increase when the nodule count increases. Surface roughness improves slightly as nodule count increases and workspeed decreases. This tendency is more noticeable when depth of cut decreases. The arithmetic mean roughness (Ra) values obtained were always below 0.8 μm.

Keywords: Thin wall ductile iron; Grinding; Residual stresses; Distortion; Surface roughness

1. Introduction

On manufacturing mechanical parts, several examples of re-engineering can be currently found, evidencing a strong tendency towards part weight reduction in order to lower costs. Wall thickness reduction and process adoption for near-net-shape parts production are two viable options to achieve this aim, as they demand lesser amount of material and reduce the machining work.

Thickness decrease generally leads to stiffness reduction unless the material is replaced by a more resistant one, so that no structural integrity deleterious effect occurs. Ductile iron has only recently been used in thin wall part manufacturing. If compared with conventional thicknesses, thin wall ductile iron parts yield both greater nodule counts and microstructural refining, and as a consequence, mechanical properties can increase. Nevertheless, the soundness of thin wall parts strongly affects the properties [1]

For severe service conditions, surface quality needs to be improved finishing the casting final dimension by means of a high precision machining process, often making use, of the grinding process.

Since thin wall parts have greater surface–volume ratio, more significant and relevant machining mechanical-thermal effects take place on the surface. Characteristics such as type and magnitude of residual stresses, distortion, roughness, plastic deformation and hardness alterations could affect loading capacity, wear behaviour and fatigue resistance, increasing the probability of parts being scrapped [2].

The magnitude and orientation of grinding residual stresses as well as the resultant distortion depend on grinding operation type, wheel, grinding conditions, workpiece material shape and size and residual stresses resulting from both prior heat treatment and machining [2,3].

In abrasive processes, the workpiece-wheel contact area can reach very high temperatures and thermal gradients, producing tensile residual stresses during the rapid cooling

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process upon the contraction of the heated area (thermal effect) [3–5]. The lower the triple product ($k\rho c$) of thermal conductivity, density and specific heat of wheel and workpiece material, the greater the stresses. In turn, if hardness, material specific cutting energy [6], and removal rate are greater, an increase in stresses is more likely.

Concurrently, surface and sub-surface layers get plastically deformed during grinding, leading to compressive stresses [3] of a sign opposite to those resulting from the thermal effect. In summary, the combined effects of the material, wheel characteristics, grinding conditions and coolant fluid lead to compressive, tensile or null surface residual stresses.

As a general rule, in grinding with coolant fluid and low removal chip rate, a better surface finish can be obtained, with both less plastic deformations and lower residual stresses [7,8]. At the same time, the chances of crack initiation and propagation reduce, improving the structural integrity and fatigue resistance of the parts [9].

The use of ductile iron in thin wall parts manufacturing, of high accuracy and stiffness requirements, is still incipient and the methodology applied is mostly empirical. Besides the information available on this topic being scarce, there are only reports of preliminary studies carried out on grinding of thin wall ductile iron [10]. Therefore, it is essential to assess the influence of the material properties and grinding conditions on surface characteristics, due to its relevance to industrial manufacturing and part performance.

This work studies grinding effects on microstructure, shape distortion, residual stresses and surface roughness of thin ductile iron plates of different nodule count.

2. Experimental methodology

2.1. Materials

Ductile iron employed in the present work was produced in a medium-frequency induction furnace of 55 kg capacity. The melt was conventionally nodulized and inoculated. Several 2 and 4 mm thick plates and 12.7 mm Y blocks (ASTM A395) were cast in sand moulds in order to obtain samples with three remarkably different nodule counts.

The chemical composition (wt%) of the melt was: $C = 3.58$; $\mathrm{Si} = 2.73$; $\mathrm{Mn} = 0.23$; $S = 0.04$; $P = 0.41$; $\mathrm{Mg} = 0.039$. This was determined by using spark optical emission spectrometry.

The nodule count was determined by means of digital image analysis. Nodule counts of 600, 1200 and 1500 nod/mm^2 were obtained for the Y block samples and the 4 and 2 mm thick plates, respectively. In all cases the nodularity ranged between 90% and 95% (ASTM A247).

2.2. Samples

Test samples are schematically represented in Fig. 1. They were cut and squared off to dimensions of

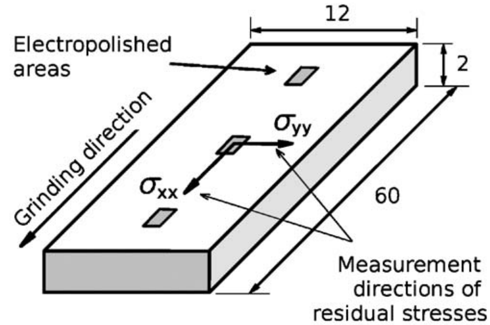

Fig. 1. Test sample scheme. Dimensions in (mm).

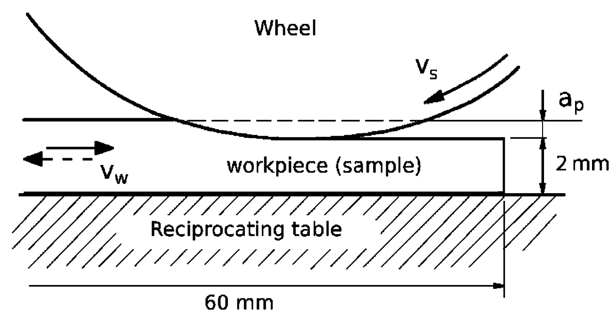

Fig. 2. Wheel–workpiece contact geometry.

60×12 mm, and afterwards recessed by mechanical shaping until reaching 2 mm thick. Low-energy cutting conditions were applied in order to minimise residual stress generation.

Before the final samples preparation stage, the material was ferritised in a furnace at 910 °C. By doing so, the matrix was homogenised and possible as-cast carbides were dissolved, leaving the nodule count as the only variable of study. The ferritised material remained with compressive residual stresses at the surface. The range of values measured by X-ray diffraction were: (−95/−139); (−180/−205) and (−281/−318) MPa for 600, 1200 and 1500 nod/mm^2, respectively. These values are considered as the initial condition of the material stress state.

Finally, the plates were manually polished to obtain both uniform thickness and surface quality. A total of 24 samples were employed.

2.3. Grinding

Conventional straight surface grinding experiments were carried out on a peripheral surface grinder with a horizontal spindle and reciprocating table. The wheel–workpiece contact geometry is depicted in Fig. 2. Finishing, roughing and abusive conditions were employed and applied to different nodule count samples. Workspeed values (v_w), depth of cut per pass (a_p) and wheelspeed (v_s) are shown in Table 1. The $a_p = 0.07$ mm value exceeds the depth of cut range commonly used in industrial production, it is considered as an abusive condition being employed in this study only for experimental purposes.