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In-process detection of surface porosity in machined castings

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ABSTRACT

Surface porosity is a common problem encountered while machining castings that contain volume porosity in the immediate subsurface. Consequent to the removal of the outer layer of the workpiece during machining, porosity that was hitherto latent in the component volume gets exposed on the generated surface in the form of a cavity. Such porosity is detrimental to the function and performance of the component with adverse cost and quality implications, if they happen to be on a bearing or sealing surface. To this end, this paper presents a novel non-contact technique that entails a pneumatic sensor for the detection of intermediate and macro-level surface porosity. The system facilitates selective inspection of surfaces including internal ones such as bore holes, and is inexpensive, flexible, and maintenance-free. It is further well suited for in-process monitoring in a machine tool environment as the hardware is simple enough for direct integration into a cutting tool holder, and the air jet cleans the inspected surface thus rendering it insensitive to cutting fluid and machining debris. The sensor performance is characterized in terms of supply pressure, stand-off distance, porosity size and speed of the inspected surface. The capability of the system for in-process application is demonstrated.

1. Introduction

Metal casting is a staple operation in the manufacture of high-volume components, particularly in the automotive and aerospace industries. Porosity defects that relate to the solidification of the metal in the die/mould are a serious quality issue in cast components. Numerous factors such as the work material, flow conditions during pouring, casting pressure, cooling rates and part geometry affect the nature and extent of porosity in a casting, which renders the process difficult if not impossible to control. The formation of porosity can primarily be due to the mechanisms of gas nucleation and shrinkage. The creation of gas porosity is understood to occur by the trapping of air or by the nucleation of gases such as hydrogen at material inclusions. Shrinkage porosity can be induced from unfavorable flow conditions in the liquid or the interdendritic feeding regions of the casting. This can be due to solidification induced cut-off of the feed passage that starves the solidification front, which gives rise to surface-linked or internal porosity.

The level of porosity within a casting is typically measured in terms of a volume percentage, and is generally determined by measuring the apparent volume; this method, however, provides little insight into either the size of the pores or their distribution. Porosity at a level of 1% could correspond to a rather large scale, ranging from 10 pores/ml for a 1 mm diameter pore to 10^7 pores/ml for 10 μm diameter pores [1]. Pores less than 5 μm in diameter are referred to as micro-porosity whereas pores larger than 1 mm are considered macro-porosity. Pores in the macro and intermediate size ranges are a challenge in terms of quality control, as their formation and distribution are not quite predictable; they are also more of a detriment to the function of the casting, and hence constitute the focus of the present work.

The casting process is ideal for the relatively inexpensive manufacture of geometrically intricate parts. However, in most applications, cast components are subject to secondary machining operations in order to fulfil functional requirements relating to dimensional accuracy, geometric form and surface finish. Surface porosity is a common problem encountered while machining castings that contain porosity in the immediate subsurface. Consequent to the removal of the outer layer of the workpiece by machining, a porosity that has hitherto been dormant in the component volume gets exposed on the generated surface in the form of a cavity (Fig. 1). Such occurrences can affect the function and performance of the component, if the porosity happens to be on a critical bearing or sealing surface, for example.

Castings can be inspected non-destructively using X-ray techniques that can reveal the size and distribution of the pores; however, depending on the application, implementation of such can be prohibitively expensive. In many instances, this may not even be warranted as porosity other than those close to the surface may not pose a problem in the first place; indeed, even surface porosity, depending on their location on the component, could be permissible if they do not interfere with the component function. Castings could alternatively be inspected for surface

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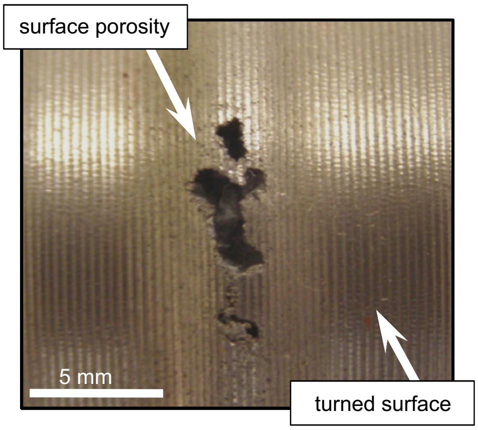

Fig. 1. Surface porosity on the machined surface of a casting.

porosity post-machining, but this has severe cost and quality implications especially in the automotive sector, wherein a large number of castings are subject to several serial machining operations in transfer lines, which represents significant cumulative value addition. If surface porosity is not detected in-process and in real-time, should a porosity appear on a critical surface earlier on in the process chain, the component is inadvertently still subject to further value addition, which is eventually lost as the component is ultimately destined to scrap, having not met surface porosity specifications. Implementing in-process inspection further allows the assessment of each and every component with no adverse influence on the cycle time, as opposed to having to rely on post-machining sampling, thus improving the overall quality of the product.

To this end, this paper details an innovative pneumatic technique that enables non-contact, in-process detection of intermediate and macro-level surface porosity. The system is simple and inexpensive, and can easily be integrated into a cutting tool for the real-time inspection of a machined surface, and is hence attractive from the point of view of application in an industrial setting. A brief review of alternative techniques [2] that could possibly be used for detecting surface porosity is provided in the following with a view to placing the proposed pneumatic technique in perspective.

2. Plausible technologies for surface porosity detection

One approach to detecting surface porosity is to employ computer vision systems that have recently gained popularity owing to the availability of sufficient and affordable processing power in modern personal computers. These systems involve an illumination source and one or more charge coupled device (CCD) cameras as well as imaging hardware and software to recognize programmed features. The reliability of the inspection process is strongly dependent on the quality of the images acquired, and hence component cleanliness and lighting are crucial, which are difficult to maintain in a machine tool environment, especially for in-process inspection. As the process is digital, the speed is further limited by the frame rate of the camera. For instance, in the in-process detection of surface porosity in a turning operation that involves a cutting speed of just 60 m/min, a porosity of size 1 mm would translate past the field of vision in 10^{-3} s, necessitating the use of expensive high speed cameras, which limits the applicability of the technique.

Point triangulation employs a laser source and a detector positioned at a set distance and a triangulation angle around 15–35° to register changes in the distance between the point of incidence of the light beam on the workpiece and the sensor. A variant of this technique is the light section method, wherein a line is projected onto the workpiece surface and a CCD matrix is used for detection. Similar to point triangulation, any deviation in the distance from the workpiece to the camera along the projected line results in a position change on the matrix. These systems have typical working distances ranging from 1 mm to 1 m, and a resolution less than 1 μm. The relatively high cost of such systems notwithstanding their effectiveness is severely limited by workpiece cleanliness, roughness and reflectivity issues.

Eddy-current sensing is a non-contact, electrical method, the principle of operation of which is based on the disturbance of the eddy-current flow lines in the field of influence of a coil with an AC excitation, on encountering cracks/flaws at the workpiece surface. This process is capable of resolution as fine as several nm and a fast response. The limitations of this technique are that (i) the workpiece material needs to be electrically conductive, (ii) recalibration is necessary for different workpiece materials, and (iii) special electronics are required for temperature compensation. This technique has been used for the post-process detection of cracks in ground surfaces; however, there do not seem to be any applications reported for the in-process inspection of machined surfaces, arguably due to the difficulty in implementing it on a machining center.

Ultrasonic sensing of a workpiece is accomplished using the cutting fluid as the coupling medium for an ultrasonic signal traveling between a sensor and the workpiece. This technique can be used at cutting speeds up to 200 m/min, and is not affected by machining debris as the stream of cutting fluid continually cleans the surface. The drawback to this technique is the requirement for a clean, bubble-free and continuous stream of cutting fluid, as changes in the coupling agent can strongly impact the system output. This system is hence not applicable to monitoring dry machining applications and minimum quantity lubricant processes that are of late becoming widely prevalent. Ultrasonic systems also require specialized equipment for signal handling and analysis, as well as for filtering and controlling of the cutting fluid, which render them less disposed to widespread adoption in industry.

3. Proposed technique

In the present work, the principle of pneumatic gauging was successfully extended to the in-process detection of surface porosity in machined castings. The application of pneumatic sensors in gauging is well established and has extensively been practiced in the industry since long [3,4]. Pneumatic measurement of displacement has largely been employed in static or quasi-static applications to do with dimensional measurement, assessment of geometric form attributes such as flatness and circularity, and to a limited extent in the characterization of surface roughness [5,6]. The technique has also been utilized in the dynamic control of workpiece diameter in a turning operation [7], and work of late has focused on improving the response time of pneumatic gauges [8]. Special applications of the principle have been realized in the metrology of biological matter [9] and foodstuff [10], and in the determination of mass transfer coefficients [11].

The principle of the pneumatic sensor can be explained with reference to Fig. 2. Air is supplied at constant pressure p_s through a control orifice to the variable pressure chamber and then on to the atmosphere via a nozzle, so as to impinge upon the work surface that is in its close proximity. Any change in the distance x_i between the nozzle and the workpiece due to their relative