A.1 Feasibility Study of Infrared Detection of Defects in Green-State and Sintered PM Compacts

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OBJECTIVE

The objective of this research is the development of an IR-based NDE technique that will enable one hundred percent quality assessment early in the P/M manufacturing process. To achieve this goal we have designed and tested an apparatus that is capable of detecting surface and sub-surface flaws in green-state compacts. The theoretical approach is based on the concepts of heat flow, i.e. thermal energy that is generated through electric current, and temperature recording over the compact’s surface. Subsequent temperature data acquisition into a computer and processing enables us to gain valuable on-line information regarding part integrity as well as process stability.

The research involves the theoretical study of heat deposition and transport mechanisms that set the baseline for our testing system. Concomitant computational modeling permits an assessment of the limitations inherent in the methodology; it allows us to critically validate the inspection approach. We tested complex parts with subsurface defects exposed to induction heating in an effort to achieve high-resolution imaging and real-time processing. Two systems are being completed:

- An off-line inspection system that is based on the principles of pulsed thermography whereby the PM specimen is subjected to a heat pulse (or step input) that is synchronized with a detection system, and
• An on-line inspection system that relies on natural convection to exploit the natural cooling of the parts in real time as they leave the compaction press.

The milestones identified by our focus group members for this spring meeting include:

A) to continue the theoretical study, including the examination of all material and geometrical parameters and all physics models (electromagnetic coupling and heat transfer),

C) to test the stability of a new, non-contact heating method and its viability in detecting subsurface defects and hidden cracks in complex parts,

D) to validate the method in real-time and in a manufacturing setting by testing defective parts of different shapes and material composition,

E) to explore new image processing methods to provide rapid and reliable feedback, and

F) to initiate a patent search to establish the novelty of this research methodology.

APPROACH

The PMRC focus group members identified four major tasks to be conducted during the fall 2005 - spring 2006 time period. Specifically, they involve:

• testing of defective parts on-line to ensure reliable detection of common cracks in a manufacturing setting,

• evaluation of our basic testing system with aluminum compacts, where high reflectivity and cooling rate pose unique challenges,

• exploration of induction heating and the design of an appropriate coil that will allow uniform heating of a part placed on a conveyer belt, and

• further investigation of adequate data analysis algorithms which can perform advanced image analysis of the compacts.

ACCOMPLISHMENTS

The researchers can report the following accomplishments:

• The theoretical investigation is converging towards a comprehensive solution that allows realistic temperature predictions over the part geometry and in the presence of defects.
• The design, construction, and testing of various custom-designed coils in combination with a commercial induction heating system was carried out. Synchronizing this system with an IR camera and a computer system through electronic circuits allowed us to construct a complete pulsed thermography system.

• Preliminary testing of aluminum parts were conducted at Metal Powder Products in St Marys, PA. These tests proved that the method is applicable to any material without major modifications. It became apparent that the aluminum parts require active IR testing or an unobstructed access to the compacts as they exit the press (due to high cooling rate).

• More general, qualitative on-line testing were carried out at Metal Powder Products with complex multilevel gears with hidden hairline cracks in the level transition.

FUTURE WORK

For the next quarter we intend to:

• Finalize the theoretical study and the modeling to provide a full model that includes defect simulations,

• Complete a statistical study to establish the detection limits. This study include, steel and aluminum parts with surface and subsurface defects,

• Design of a user-friendly software package for the data analysis that will enable the operator a reliable pass/fail feedback. In addition, the software will enable a more comprehensive failure analysis by providing defect features.

• Refine the available system for a manufacturing setting and for usage by manufacturing staff.

REPORT ORGANIZATION

Appendix A contains the technical data from our testing at Metal Powder Products. Specifically, an overview of the data collection is presented and a basic thermal analysis is shown that describes the versatility of the method.
ACKNOWLEDGEMENT

We would like to extend appreciation to our focus group members for their guidance and their important input throughout this project period. In particular, we would like to thank Dr. Chaman Lall (Metal Powder Products), Richard Scott (Nichols Portland) and Dr. Ian Donaldson (GKN Sinter Metals) for providing access to their facilities to conduct extensive on-line testing. Their help in furnishing of samples and providing manufacturing related insight proved invaluable.

We would also like to thank Dr. Hannes Traxler (PLANSEE Aktiengesellschaft) and Ulf Gummeson for their continued support and their encouraging remarks during the execution of this project.
ON-LINE TESTING AT METAL POWDER PRODUCTS

Tests at various manufacturing facilities allowed us to establish the stability of our inspection system and its immunity from temperature fluctuations in the plant arising from production equipment such as presses, motors, and sinter furnaces. We have also demonstrated that the system is capable of collecting “clean” thermal data from a process line producing complex multi level gears at high speed. The camera system was capable of focusing and imaging at a high frame rate allowing comprehensive data analysis both in time and in space.

It is therefore necessary to validate the IR system for the detection of real and commonly observed defects in the process line. Furthermore, our plan to extend the usability of this method to detect defects regardless of material composition requires careful analysis. Aluminum presents a unique challenge: it is a highly reflective material with very low emissivity (0.1 to 0.2) when compared to steel parts with high graphite content where the emissivity is of the order of 0.6.

The tests presented were performed at two facilities of MPP in St Marys, PA. Figure 1 shows the green-state P/M sample. The compact is a two level gear with 13mm in height by 60mm in diameter and is typically manufactured at a rate of approximately 600 parts per hour.

![Figure 1: Picture of a green-state P/M part to be tested at MPP.](image)
The following IR images in Figures 2 and 3 represent 2D surface and line profiles (recorded along the dotted line) of parts that are expected to be defect-free. The images are recorded with an IR camera positioned 50cm away (viewed from the side) and operated at a frame rate of 30Hz. The field of view of the 240 by 320 pixel viewing is 15cm by 15cm. The total line length of 10cm is subdivided into 180 points (i.e. with a point-to-point resolution of 0.5mm) whereas the thermal pixel intensity is displayed in discrete increments from a baseline of 0 (or 200K) to 260 (or 460K).

![IR Image](image1.png)

**Figure 2:** (a) First image from the IR recording of the gear shown in Figure 1 at a speed of 0.13m/s, and (b) thermal profile along the dotted line.

A long IR image sequence of 45 seconds generates 1350 recorded temperature points with an intensity profile depicted in Figure 4. As expected, as soon as a compact moves past the fixed spatial sensing location, the temperature increases. Figure 3, shows the location of the temperature tracking point.

![IR Image](image2.png)

**Figure 3:** Temperature monitored at the point shown.
**Figure 4:** Temperature (in K) recorded at a fixed spatial location (one spot) over time.

Zooming into the data sequence reported in Figure 4 allows us to conduct a more detailed analysis, as depicted in Figure 5.

**Figure 5:** Temperature (in K) recorded at a fixed spatial location (one spot) over time.

Apart from some small variations, the temperature profiles are reproducible. This is consistent with the fact that the parts are defect-free, an observation that was verified off-line. Therefore, we attribute the thermal fluctuations to instabilities in the process.
The IR images in Figure 6 are taken at the same line as the images shown in Figure 2. However, here the first 20 sec show defective parts and later the process had to be adjusted to eliminate the defects. Below is an IR image of a defective gear and the associated profile along the dotted line.

![IR image and profile](image)

**Figure 6:** (a) Second image from the IR recording of the gear shown in Figure 1 at a speed of 0.13m/s, and (b) thermal profile along the dotted line.

It is apparent that the profile shown in Figure 6(b) differs from the profile shown in Figure 2(b); this is a key indication for the presence of a defect. For processing in the case of significant defects similar to what is presented a simple image subtraction would be sufficient to flag the flaw. The statistical analysis that shows a full 45 sec inspection duration, or 1350 frames, is depicted in Figure 7. Defects were introduced by changing press settings while operating; Figure 7 depicts the points were the process was modified.

![Temperature graph](graph)

**Figure 7:** Temperature (in K) recorded at a fixed spatial location (one spot) over time.
A detailed investigation of the data sequence reported in Figure 7 allows us to conduct a more thorough analysis, as depicted in Figure 8.

![Graph showing temperature over time](image)

**Figure 8:** Zoomed-in temperature (in K) recorded at a fixed spot location.

As can be seen by directly comparing Figure 5 with Figure 8, several parts are defective. Detailed image processing techniques that allow us to flag the defective parts will be discussed with our membership. As a result, this methodology has the potential of becoming a very simple, yet reliable methodology that allows us to identify defective parts in an on-line setting.
Additional tests that involve aluminum parts are discussed below. The testing was also conducted at MPP in St Marys, PA. Figure 9 depicts the green-state aluminum powder part. The compact is 20mm in height by 50mm in length and 15mm in width, a high density (part parameters and material composition are proprietary to MPP), and is manufactured at a rate of approximately 900 parts per hour. Aluminum compacts provide unique challenges of high emissivity and high cooling rate. They, therefore, require special attention with regard to viewing angles and part access in close proximity to the press. It is also important to ensure temperature equilibrium during the testing phase.

**Figure 9**: Aluminum powder green-state compact.

Due to access restrictions we were unable to image the green-state compacts directly as they exited the press. This unfortunately precluded our ability to inspect the parts while they are at a high temperature setting. For the testing, we use the same procedure by selecting a fixed sensing point in the process line as shown in Figure 10. We can then monitor its temperature behavior over time.

**Figure 10**: Identifying a point (cross) in the process line for thermal recording.
As discussed before, we can now examine defect-free and defective parts with artificially induced hairline cracks across the curved section of the compact. First, we report the statistical data for the defect-free parts in Figure 11.

![Graph](image-url)

**Figure 11:** Temperature (in K) recorded at a fixed spatial location (one spot) for defect-free aluminum compacts.

Defective parts are shown in Figure 12. In the thermal response it is difficult to observe the effects of the crack in the surface temperature profile over the compacts. This is mainly due to the fact that the compacts do not reaching thermal equilibrium. However, we can still discern a baseline variation which could be indicative of process changes that may have caused the defects.
CONCLUSIONS

The data collected at both facilities of Metal Powder Products confirm the fact that the IR testing methodology is easy to implement in a manufacturing setting and poses little intrusion, or changes, to the fabrication process. Preliminary testing suggests that the IR imaging system is relatively immune to changes in the background noise generated by the manufacturing equipment.

Our very early data collection supports the fact that we can detect defects in a real time environment. Therefore, we are confident that this system will ultimately be capable of performing a 100 percent quality assessment of the green-state P/M compacts by providing real-time operator feedback. Additional information about defect parameters can also be extracted for engineering purposes and for process calibration.

In addition to fabrication immunity, the IR testing methodology appears sufficiently robust to handle different material compositions. In particular, we are able to test aluminum parts that have the special characteristics of high reflectivity and high cooling rate.

Thus far, all of our signal processing and data analysis is performed off-line. For a fully manufacturing-compliant system it is important to combine these steps into a rapid data collection and processing environment to provide real-time feedback.