CO2 cleaning technology for cleaning micro-/nanostructured inserts:
The IMPRESS FP7 Project

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Abstract

As part of the seventh framework program, the IMPRESS project focuses on the development of a technological injection molding platform for the serial production of plastic components with incorporated micro- or nano-scale functional features. The platform is based on the acquisition of up-to-date, highly advanced facilities/information based on three main modules, each being a tool box made up of several building blocks.

One of the blocks is the CO2 cleaning technology for cleaning micro-/nano-structured inserts. Requirements regarding cleaning processes for such injection-molding tools, i.e. ensuring the reliable and gentle removal of particulate and filmy contamination in the micro- and nanometer range, are fulfilled using the CO2 snow cleaning method. The development of an innovative CO2 nozzle technology combined with a highly-clean compact media supply unit for the cleaning gases enables automated, robot-controlled cleaning directly in the opened mold. Depending on cleaning requirements, this means that injection-molding inserts no longer have to be removed with the result that cleaning times are shortened and recontamination risks after cleaning minimized.

Keywords: CO2 cleaning technology; CO2 snow cleaning, micro-nanostructures, injection molding, platform.

1. CO2 snow jet cleaning technology

In the manufacture of micro- and nanostructured plastic injection-molded parts, the cleanliness of an injection mold plays a decisive role regarding the quality of the finished product. Therefore, the injection molds or mold inserts have to be cleaned at regular intervals in order to ensure the flawless molding of ultra-precise structures. Within the scope of the IMPRESS project [1], the cleaning process must fulfill two main requirements:

- Effective but gentle removal of particulate and filmy micro- and nano-sized contamination from the structured inserts of the injection molds.
- Possibility of integrating the cleaning process into the injection-molding machine to avoid having to remove injection molding tools in order to carry out the cleaning process. This would enable an integrated cleaning step to be performed after each injection-molding process, or cleanliness controlled by a (contamination) sensor.

The cleaning process with CO2 snow is ideally suited to fulfill both of these demands. By combining mechanical, thermal and chemical solvent effects, a wide range of surface contamination can be removed. The sublimation impulse technique developed at the Fraunhofer IPA in Stuttgart, Germany, is currently the most effective CO2 snow-based cleaning method worldwide. Because CO2 sublimes in the gas phase after the cleaning process, there is no further need to dry the cleaned surfaces. This allows the process to be carried out directly at the level of the injection-molding machine without having to remove the injection-molding tools or inserts.

CO2 is a gas which is non-combustible, non-corrosive, non-toxic. The CO2 gas for this applications is generated during industrial processes as a waste gas as an environmentally friendly gas.

1.1. Cleaning process – functional principles

To generate the cleaning crystals, liquid CO2 is expanded in a nozzle causing it to cool severely and form fine snow crystals. In the two-component nozzle utilized, compressed air is added via an annular gap to form a jacketed jet around the core of CO2 crystals, accelerating them to supersonic speed. This is necessary in order to give the CO2 snow crystals the impulse required to enable them to clean efficiently. The low degree of hardness of CO2 snow crystals also ensures that surfaces are cleaned gently. This enables a broad spectrum of particulate and filmy contamination to be removed in a highly-precise and environmentally-neutral way without the need for additives.
1.2. Cleaning process – effects

The cleaning process using CO2 is based on a combination of several effects [2] this is shown in Figure 1:

- The accelerated snow crystals transfer an impulse to the contamination particles (sandblasting effect).
- Thermal tension is triggered between the surface and the contamination (thermo effect).
- The surface is rinsed as a result of the 600x increase in volume as the CO2 sublimates (rinsing effect).
- In its hypercritical state, CO2 dissolves filmy contamination; the solvent effects are comparable to those of cyclohexane (C6H12) (solvent effect).

1.3. CO2 – advantages of snow cleaning

As well as the excellent cleaning ability due to the combination of the cleaning effects described, the use of CO2 snow also has further advantages as far as its application inside an injection-molding machine is concerned [3]:

- The use of a compact cleaning nozzle in a dry, residue-free cleaning process makes the method ideal for automated integration into an injection-molding production line. After opening the injection mold to remove molded parts, a robot arm could be used for example to clean the injection molding tools or inserts without further steps being required. Compared with other conventional mechanical or liquid-based cleaning methods, this represents a milestone as far as quality and short processing times are concerned.
- Especially with regard to the micro- and nanostructured surfaces of injection molding inserts, by altering the size of the snow crystals via a suitable parameter set-up the cleaning effect of the CO2 technique can be finely adjusted. Such surface structures can otherwise only be cleaned in ultrasound or megasound baths and cannot be carried out inside an injection-molding machine.

2. Nozzle technology

2.1. State of the art CO2 nozzle technology

Current state-of-the art CO2 cleaning nozzles have a standard Laval geometry and are made to withstand a pressure of 10 bars for the jacketed jet of compressed air. Figure 2 shows examples of single nozzles and Figure 3 a nozzle array, which is used to efficiently clean larger surfaces.
The CO2 nozzle technology allows very fine crystals to be produced. This was ascertained using a test bench consisting of a CO2 capillary and a laser diffraction measurement instrument. Fig. 4 shows that 15% of all snow crystals were below 1µm in size and the remaining 85% below 10µm. This ensures that contamination present inside micro- and nanostructured surfaces is reached and removed by the impulse of the snow crystals.

2.2. Optimization of nozzle design

To further enhance cleaning efficiency regarding micro- and nanostructured injection molding inserts, the fluid dynamic design of the CO2 nozzle was improved. The aim was to increase the velocity of the CO2 snow crystals by accelerating them with the aid of the jacketed air stream. This was achieved despite decreasing the pressure of the compressed air supplied. As a result, the optimized nozzle can work with standard compressed air networks without the need for an additional pressure booster.

By carrying out fluid dynamic computer simulation on different Laval geometries, it was possible to calculate and increase the velocity of the compressed air flow at the nozzle exit. The velocity of the CO2 snow crystals could be enhanced immediately, thus enabling cleaning efficiency to be optimized at lower compressed air pressures.

The CO2 nozzle improvement is realized by the optimization of the Laval geometry by the inner geometry (Fig. 6 green part in the right picture of existing standard nozzle) and the outer geometry (Fig. 6 brown part). With this optimization the speed of the CO2 snow particles by higher compressed air speed was realized.

2.3. Evaluation of new nozzle design

Tests were performed on Styrofoam blocks in order to visualize the higher cleaning impulse of the CO2 snow crystals attained with the new nozzle design. The higher degree of abrasiveness of the CO2 jet from the new nozzle made a much deeper impression in the Styrofoam blocks than that achieved with standard nozzles, as can be seen in Figures 7 and 8 with the two different pressures used. With this test method, the efficiency of the new nozzle design could be easily demonstrated and the compressed air supply system pressure decreased while maintaining high cleaning efficiency.
3. Adaptation of the CO2 technology to injection molding

3.1. CO2 media supply technology

In order to be able to integrate the innovative CO2 cleaning process into an injection molding machine, a compact and autonomous CO2 media supply was required. As part of the IMPRESS project, we designed and realized such a media system and implemented it in the IPRESS platform. The media supply is made up of the following components and is capable of supplying one or a nozzle array:

- Media main + process valves for CO2 and compressed air
- Particle filtration of compressed air to 0.01µm
- Hydrocarbon filtration for compressed air down to 0.005mg/m³
- Particle filtration of CO2 down to 0.01µm
- Pressure regulator for compressed air
- Pressure sensor for CO2 and compressed air
- PLC / optional decentralized PLC module
- CO2 cooler

3.2. Robot adaptation

Automated cleaning with robot-controlled CO2 nozzles or nozzle arrays has already been realized in a number of applications and is utilized successfully in industry.

However, it is a new innovative and resource-efficient concept to integrate the technology into an ultra-precise injection molding process and to control cleaning with the aid of a trigger set by monitoring process parameters and product characteristics.

After integrated into the IMPRESS platform, the robot - a Stäubli RX 160 – will introduce the CO2 cleaning tool into the open form immediately upon completion of the injection-molding process and removal of the component produced. This means that the cleaning step can be carried out without the need for additional service tasks or downtimes.

4. Cleaning validation

4.1. Tests on model substrates

In order to validate the cleaning efficiency of the new CO2 nozzle in the micro- and sub micrometer range, a procedure was applied which had been developed to validate the cleaning of ESA (European Space Agency) flight hardware components. The procedure is composed of the following steps [4]:

Step 1: Rough cleaning - solvent
Step 2: Pre-conditioning – ultrasonic cleaning
Step 3: Application of contamination – spraying on micro silver particles
Step 4: Contamination charge (before) - automated SEM
Step 5: Cleaning process - CO2-snow cleaning
Step 6: Contamination charge (after) - automated SEM
Step 7: Contamination reduction - calculation

Silver particles approx. 1µm in size were utilized as test particles. Silver was suitable for several reasons.

Firstly, it provides the high material contrast required for automated counting using a scanning electron microscope SEM. Secondly, as it is not generally present in typical environmental contamination, the...
influence of cross-contamination on test results can be excluded. The cleaning efficiency regarding micro silver particles compared to “normal” contamination particles was correlated by measuring particulate forces of adhesion. To do this, a micromanipulator, a spring table and force measurement manufactured by Kleindieck were integrated into a scanning electron microscope and utilized. The table is capable of measuring particle adhesion forces as low as just a few nano-Newton.

4.2. Tests with MNF mould inserts with microneedles

4.2.1 Test procedure

To measure the injection molded parts with regard to shape, surface roughness and absence of residues, a 3-D measuring system with a vertical resolution of up to 10nm manufactured by Alicona was implemented at the Fraunhofer IPA.

4.2.2. Tests on used (soiled) and cleaned inserts

The tests were performed on Ni MNF mould inserts with a microneedle design and supplied by CARDIFF UNIVERSITY after they had used them for an injection molding test with polycarbonate (PC).

The first test on used microneedle molds (Fig. 13 left and Fig. 14) showed that the needle mold was blocked by residues of plastic. After cleaning (Fig. 13 right and Fig. 15), it was possible to assess the complete needle mold right down to the bottom without finding any residual particles. To get an impression of the view inside the insert with plastic particles (Fig. 13 left), the 3-D model from the cleaned insert was combined with the reference data points from the used insert.
5. Conclusions

A CO2 snow cleaning station has been developed, realized and tested for integration into an injection molding machine for micro- and nanostructured plastic components. To achieve this, an innovative CO2 nozzle was designed which enables parts to be cleaned more efficiently at a lower operating pressure. Cleaning efficiency down to the submicrometer range was ascertained both on models and on real contamination. An optical 3-D measurement procedure was implemented successfully to assess used and cleaned injection mold inserts utilized to fabricate microneedles. The robot-controlled application directly at the level of the IMPRESS platform injection molding machine is currently under construction at the Pôle Européen de Plasturgie (PEP).

Acknowledgements

We kindly acknowledge our thanks to the European Community for funding the IMPRESS project.

References


