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Robust Control using Sliding Mode Approach for Ice-Clamping Device activated by Thermoelectric Coolers

Alexandra Mironova, Paolo Mercorelli, Andreas Zedler

Institute of Product and Process Innovation
Volgershall 1, D-21339 Lueneburg, Germany
(e-mail: {mironova, mercorelli, zedler}@uni.leuphana.de)

Abstract: By virtue of high quality standards, work holding devices play an important role in machining processes. Especially thin-walled and fragile parts in the micro manufacturing, but also free formed and irregular shapes in the macro manufacturing are difficult to clamp without deforming. In order to face these challenges an innovative adhesive technique is introduced and investigated in this paper: clamping with ice. In order to investigate the forces of ice-clamping, experiments were carried out and the results are shown and discussed in this paper. Analogous to mechanical force-fitted clamping jaws a definition of clamping and holding forces is introduced. Moreover, the design of a Sliding Mode controller, based on Lyapunov's approach, is proposed such that temperature disturbances caused from the machining process, like e.g. thermal energy of milling, are reduced.

Keywords: Ice-clamping, workholding device, deformation-free, thermoelectric cooler, temperature control, sliding mode control, lyapunov.

1. INTRODUCTION AND MOTIVATION

During machining processes workpiece clamping has to guarantee a secure grip to avoid the piece getting loose and remove from its clamp, for that it needs enough force fit. However, exerting too much force can lead to damages. Especially small and thin-walled parts in the micro manufacturing are difficult to clamp without deforming. In addition, in the macro manufacturing free formed and irregular shapes pose also a big challenge for common used mechanical force-fitted clamping systems, which can lead to cost-intensive pre-manufacturing of special jaws being only economically profitable for batch fabrication. To face this, there are several options in the industry to clamp these challenging parts: clamping with vacuum, with magnets, with low melting metals, with glue, wax or magnetorheological fluids. Next to the advantages of not deforming the part mechanically the disadvantages of these applications are: Clamping with vacuum requires a plane, flat, unperforated surface of the workpiece, otherwise it would not clamp. Magnetic clamping technology needs the workpiece to be magnetic or at least it has to be magnetized beforehand, which leads to pre- and post-processing. Magnetorheological fluid clamping has its limits in flat or limp parts, see Blumenthal and Raatz (2012). Also adhesive techniques such as clamping with low melting metals, glue and wax needs remachining in terms of removing the adhesive material from the workpiece afterwards. In contrast, a cleaner and sustainable adhesive method with no remachining is the technology of clamping with ice. Having water freeze under and around the workpiece, it would hold it firmly bonded no matter which form and for almost every material. Although this technique is some decades old it is still being exotic and not wide prevalent in the industry and current research, therefore it needs to be examined more precisely. This article is focused on the capabilities and application of ice-holding technique for industry meaning as well as its control. To clamp with ice, a plate with a high thermal conductivity, such as aluminium or copper, is wetted with a thin layer of water, the workpiece is putted on it and the plate is chilled to sub-zero temperatures, freezing the water to ice, which encloses form-fitting the piece and holds it in position. To freeze the plate one can use compressed air (pneumatics) or thermoelectric coolers (TECs). In case of using TECs, a heat sink with a forced cooling through air with fans can be used or a water-cooling system, which offers a better performance, but maximizes the size of the system. In order to control the temperature properly, a system with TECs is used for the experiments and the designed controller presented in this paper. Nevertheless, the measured forces do not depend on the type of cooling technique. Whereas there is, up to the best and present knowledge of the author, only a few manufacturers and distributors for this kind of technique in the market, like Spreitzer GmbH & Co. KG, Triag International AG and Witte Barskamp KG, also just a small number of researches thematize the topic of clamping with ice. This is not surprising in view of the fact that the development of this application goes back only to 1998, devised by AMCC France. Jou (2006) investigates an optimal channel design for coolant of freezing chucks and focuses his work on the water-cooling system and in Jou (2010) - the author shows a thermal analysis as a function of the thermal resistance of a single TEC. Further researches are carried out by the IfW from the University of Stuttgart, see Heisel et al.

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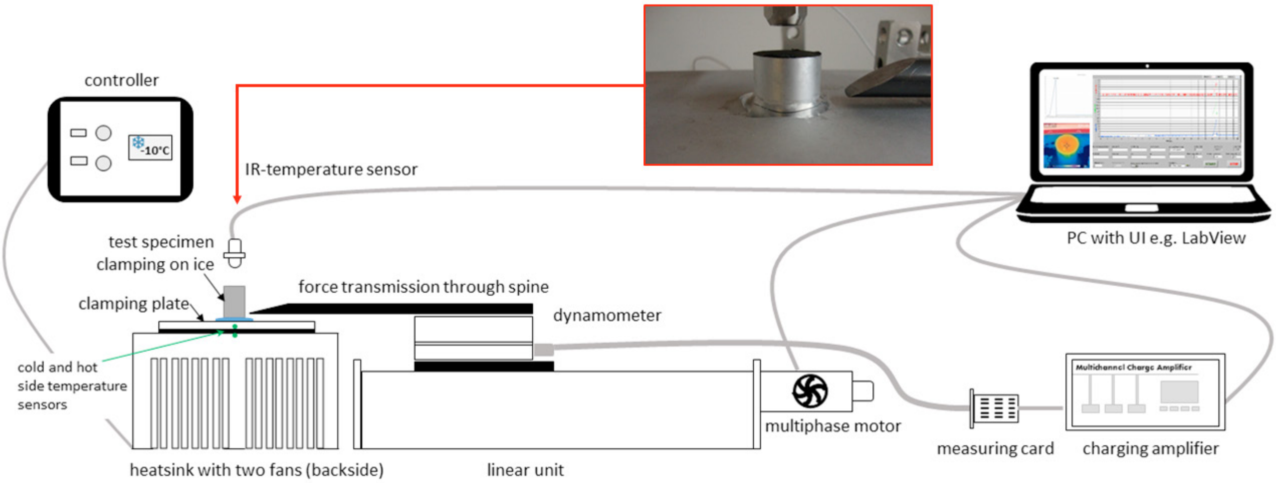

Fig. 1. Schematic view of the experimental set-up to measure the clamping and holding shear forces of ice-clamping device with a close-up photograph, highlighted in red, of test piece put in liquid water before freezing

(2014). The IfW research team investigates the holding forces, the clamping time and the static clamping strength compared with other micro clamping techniques, such as mechanical jaws, glue, wax and vacuum. Although the results of the IfW studies are promising, the concentration of their work focuses on the comparison and decision making of which clamping technique is to be used in particular micro manufacturing applications. Moreover, the results of the experiments for holding forces in ice-clamping do not indicate which material the clamping plate is made of, so that it is non-reproducible, as it is shown in this paper, the material of both, workpiece and plate, is of great significance for the clamping forces. This is also confirmed by Kitajima et al. (2004), who investigate the freezing characteristic of two kinds of clamping plate materials and found out that, due to the larger thermal conductivity, molybdenum, compared to steal SUS304, is better in terms of clamping time. The authors also compared ice-clamping to wax-clamping with reference to the cut-off characteristics, which shows that ice-clamping control the chipping and thus the crack propagation notable better than clamping with wax. In the field of control design for ice-clamping with TECs, industrial applications are limited to a PID controller, using however just the P-part of the controller. Thus this paper is focused on designing a robust controller using the Sliding Mode approach such that a temperature disturbance reduction is obtained. Temperature disturbances in this case reflect the external disturbances due to the machining process itself, like the heat generated in the material by a cutter in a milling process. For this purpose, a mathematical model of the system is generated and simulation results are shown. The challenges of designing a controller for TECs lies in the non-linearity of the system, so the common approaches focuses either on linearising, like done in Song and Wang (2012), H.-S-Choi et al. (2007), Aly and El-Lail (2006) or setting the counterpart, here the hot side of the TEC, to a fixed value, like in Yusop et al. (2013) and H.-S-Choi et al. (2007), or taking the according values from data sheets like in Wang et al. (2009). Even if the usage of fixed values or linearisation simplify the model, it reduces not only the accuracy but also the importance of the thermoelectric interacting of both sides, which namely characterizes the complicated physics. Therefore this paper focuses on modelling both sides with their own dynamics simultaneously, guaranteeing the robustness and fixing the uncertainties through Lyapunov's approach pairing with Sliding Mode. The paper is organised in the following way. Section 2 describes the experimental set-up and shows the potentiality of the system reporting some ice-clamping force measurements, showing the significance of temperature to the clamping forces and thus the need of a robust controller. Section 3 through a constructive demonstration of a theorem shows the existence of a control law and derives its mathematical structure. In Section 4 computer simulation results are presented. The conclusions close the paper.

2. EXPERIMENTAL SET-UP AND SOME ICE-CLAMPING FORCE MEASURED RESULTS

To observe the system of ice-clamping, measurements were carried out, determining the correlation between ice temperature and clamping forces. Fig. 1 shows schematically the experimental set-up, measuring the shear forces. Six TECs are affixed under the aluminium clamping plate (EN AW 5083), cooling it and thus solidifying the water droplet in order to clamp the workpiece on it. With a spine, the force is transferred through a linear unit movement vertical on the workpiece. The force, which is needed to break the workpiece out of the ice fixture, is measured by the Multi-Component dynamometer from KISTLER, saved and illustrated in LabVIEW™. Four temperature sensors are installed in the system: one sensor measuring the cold side, one to measure the hot side, one infrared thermometer above the workpiece, measuring the temperature on the top of the specimen, and one for the room temperature together with a hygrometer for the environment. Similar to the illustrated set-up, the tensile forces were measured, using a pull rope system. Additionally the torsional forces were measured. The red highlighted photograph in Fig. 1 shows the real reference test piece, made from AlMgSi0.5, with dimensions d=25 mm, F=25 N, h=19.25 mm and with an average roughness of Ra=0.5 µm , as well as the clamping plate. The top surface of the test piece is covered