

1 Introduction

According to the GERMAN MACHINE TOOL BUILDERS' ASSOCIATION (VDW), milling machines and machining centers accounted for around 32 % of all machine types in production in Germany in 2023 [GERM24, p. 22]. Due to its high geometric flexibility and productivity as well as the achievable product quality, milling is a key technology in metalworking. Examples of industries that achieve a significant proportion of their added value through milling include aerospace, die and mold making, the semiconductor industry, life sciences, and general mechanical engineering. Today, metal products are characterized by increasingly complex designs, high quality standards, and demanding functional requirements. As a result, 5-axis milling processes are increasingly being used to manufacture them, supported by advanced computer-aided manufacturing (CAM) software for process planning. The established tool technology for finish milling complex geometries, such as free-form surfaces, is milling with ball end mills (BEM) [BIEK91, p. 30]. Their spherical shape and the favourable position of the tool center point (TCP), similar to a ball joint, enable very simple geometric handling in the tool path calculation. Ball end mills can be easily guided over different surface geometries and offer great freedom in tool alignment. In addition, ball end milling operations are characterized by comparatively constant engagement conditions, which leads to favourable machinability criteria such as process forces, tool wear, process stability, and surface quality. However, the ball end milling process is very time-consuming, as the distance between adjacent tool paths must be very small in order to achieve a high surface quality.

One approach to increasing productivity in finish milling is the use of new cutting tool technologies. In addition to advances in the area of cutting material, coatings, and cutting edge preparation, more productive processes can also be achieved by adapting the macro geometric tool shape itself. An important trend in this area is the use of so-called circle segment end mills (CSEM), also known as barrel tools [BOOS18, p. 20]. Circle segment end mills are characterized by a circle segment contour visible in the lateral view of the cutting tool, the radius of which is significantly larger than the actual ball end radius of a comparable ball end mill (see Fig. 1.1). As a result, the distance between adjacent tool paths during finish milling can be significantly increased, which leads to a reduction in the required milling time and tool consumption, while achieving the same or even higher surface qualities than with ball end milling. Nevertheless, circle segment end mills are still only used to a limited extent by industrial end users and can only be found in a few milling applications. The low industrial acceptance of circle segment end mills is due to a number of technological challenges in tool path calculation, tool design, and machinability.

In terms of process design the eccentric position of the circle segment center point as well as severe restrictions in tool orientation require adapted milling strategies and tool path calculation algorithms. In addition, the tool shape itself and the interfering contours have a strong effect on the tool path trajectory. Due to the large effective radius of circle segment end mills, high and at the same time strongly alternating osculations between the cutting tool and the workpiece can occur during the process. The high osculations can lead to unfavourable effects such as double point contact or undercuts. From a technological point of view, due to the high osculations, circle segment end mills tend to exhibit considerable fluctuations in the engagement between tool and workpiece and therefore in machinability criteria such as process forces, tool wear, process stability, and surface quality during a milling process. These fluctuations impair the workpiece quality achieved and the efficiency



Figure 1.1: Ball end mill (left) and circle segment end mill (right)

of the milling process. These effects are less noticeable in the milling of simple surface geometries such as flat or ruled surfaces, but are particularly evident in the milling of complex free-form surfaces.

With regard to the described deficits, the present work aims to enable the flexible use of circle segment end mills for finish milling of complex free-form surfaces while avoiding critical process conditions. This is intended to support the industrial use of circle segment end mills in order to realize significant productivity increases in production. The fundamental investigations focus on the detailed analysis of the engagement conditions in relation to different surface topographies, process parameters, and milling strategies. A high-precision engagement simulation is modified to enable the simulation of circle segment end milling operations. The simulation functionalities are used to determine causalities for the fluctuating engagement conditions and process forces during milling with circle segment end mills. The aim of these research activities is the derivation of suitable process rules and their implementation in adaptive milling strategies, supported by corresponding aspects of tool path calculation for 5-axis milling with circle segment end mills. The validation of the CAM-integrated adaptive milling strategies is carried out using a free-form surface demonstrator.