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Method for optimizing cam workspeed utilizing Artificial Intelligence technique

Michael Skinner[1], Daniel Turner[1]

[1]*Fives Landis Ltd, UK*

Michael.skinner@fivesgroup.com

Abstract

Optimisation of a cylindrical grinding process is usually considered to be an art which relies on experts who have many years of grinding experience. This problem is made worse when grinding out-of-round components as this adds machine dynamics and non-uniform thermal limitations to an already complex situation.

As always in manufacturing, the desire to increase productivity and 'speed up' conflicts with product quality. Historically product quality is maintained at the expense of productivity, and for cams the approach has been to use a variable work-speed to slow down over complex sections to try to mitigate geometric error, or to slow where there are thermal issues to lower the metal removal rate.

This has proved difficult to solve mathematically. There are competing objectives, and the problem space is circular and continuously dynamic with no 'at rest' starting point. Consequently, the calculated work-speeds end up rather subjective and it's left to the skill and experience of the process engineers to get the most out of the grind.

We present how the problem was sub-divided such that the machine dynamics and part quality is separated out and each given a single numerical optimisation target which is ideal for an Artificial Intelligence (AI) based optimisation [1]. With the former 'solved' by AI, the later while complex, can use that as its starting point and be solved with conventional spreadsheet-like mathematics.

Patent granted 2019 [2]

AI, grinding, asymmetric profiles, optimised grinding feed rates

1. Background

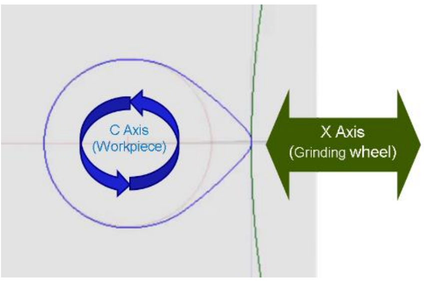

Figure 1. Cam grinding principle

In grinding operations, the workpiece typically rotates about the C-axis while the grinding wheel traverses along the X-axis. For achieving circular geometries, a steady X-axis advance leads to the desired diameter. However, complex shapes necessitate the X-axis to follow intricate contours during its movement. This requires rapid and precise control of the X-axis position.

2. The Challenge

The arbitrary nature of workpiece shapes translates to irregular, non-sinusoidal oscillation profiles for the X-axis. While moderate C-axis rotation speeds allow the X-axis to track the desired path accurately, increasing production demands necessitate higher operating speeds.

This presents a major challenge:

- **Reduced Axis Position Accuracy**: At high C-axis speeds, the X-axis struggles to follow the rapidly changing path, leading to deviations and compromised grinding quality.
- **Risk of Damage**: Sharp changes in the workpiece profile encountered at higher speeds, translate to high material removal rates, increasing the risk of burn and workpiece defects.

The key bottleneck lies in identifying the areas within the grinding profile that are most detrimental to high-speed operation. These critical sections limit the allowable C-axis speed for the entire workpiece revolution.

Fortunately, slowing down the C-axis only during these sections, instead of throughout the entire cycle, presents a potential solution, and represents the traditional strategy of creating an angular velocity profile known as a 'Workspeed'.

3. Traditional Workspeeds

The traditional workspeed strategy, involves tailoring the C-axis speed throughout the grinding cycle based on strategically slowing down only during critical sections with steep profiles. This can make a huge difference to cycle time and quality as the majority of the profile is run at 'full' speed.

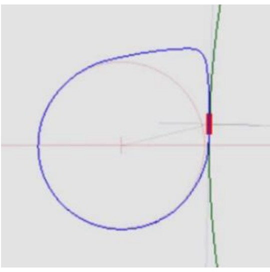

Figure 2. Cam grinding critical section – large contact region

Comparing to a constant workspeed:

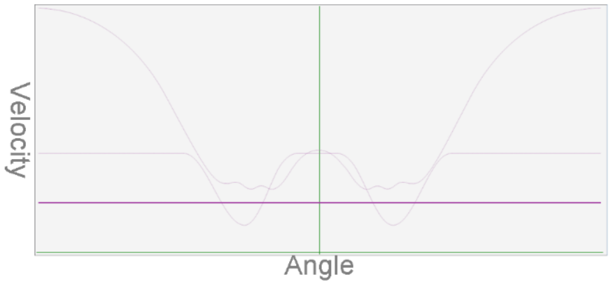

Figure 3. Constant Velocity – slowed over whole revolution

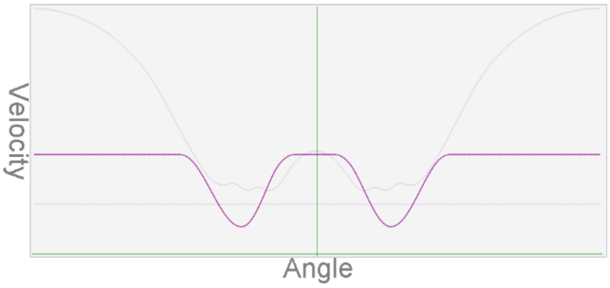

Figure 4. Slowed only over steep sections

- **Axis Position Accuracy**: Lowering the C-axis speed during peak X axis movements allows the X-axis to accurately follow the intended path, minimizing tracking errors and enhancing grinding quality.
- **Minimize Damage Risk**: Lowering the C-axis speed during peak material removal sections mitigates the risk of burn and workpiece defects.

By implementing Workspeed variation, we can leverage the benefits of high-speed grinding while addressing the limitations imposed by complex workpiece geometries. This approach has the potential to significantly enhance grinding efficiency and quality, while maintaining machine competitiveness in a demanding production environment.

3.1. Calculation

The traditional "Workspeed" approach prioritizes equalizing Metal Removal Rate (MMR) or cutting surface speed while adhering to constraints imposed by the machine and process. Avoiding burn and surface finish are the final objective, and because burn is seen as a result of MMR and therefore grinding energy, the calculations are framed such that achieving a constant MMR is the primary goal. Other factors like jerk and other high-order derivatives while important and always factored in, are often side-lined.

Within this framework, the MMR is maximized around a "base circle" (a circular section at the back of the cam). Subsequently, sections of the Workspeed profile are slowed down to maintain a constant MMR throughout the machining process. This slowdown may be further adjusted if axis constraints dictate.

3.2. Limitations

Despite offering an improvement over constant feed rate machining, the traditional Workspeed approach suffers from several limitations:

- **Oversimplification of Burn Mitigation**: Using MMR as the sole factor for burn control is overly simplistic. Numerous variables influence burn, such as material properties, tool geometry, spindle power, coolant effectiveness, and cutting speed. Relying solely on MMR for burn mitigation is inadequate.
- **Counterintuitive Effects on Burn**: Paradoxically, maintaining constant MMR to control burn can actually worsen the situation. Slowing down the tool creates a hot spot and allows more time for heat transfer, concentrating the thermal energy in a specific region and potentially exacerbating burn.
- **Mathematical Complexity**: Back-calculating the required feed rate based on axis dynamics is mathematically challenging. Jerk calculation involves solving a third-order integration, and all constraints must be simultaneously considered, further complicating the process.

Ultimately, while the traditional variable workspeed approach represents a significant advancement compared to constant workspeed machining, its results often resemble an informed guess due to its limitations. Successful application still requires significant skill and experience from a human to get right.

4. Reframing The Optimization

Traditional approaches to grinding optimization have heavily focused on optimising the workspeed as a singular solution to address cycle time and quality issues. Cutchall [3] and Krajnik et al. [4] exemplify this approach, proposing simultaneous optimization of axis dynamics, MMR, power, wheel wear, and surface temperature as constraints for a given cut depth which can then be varied to discover some kind of optimum.

Many papers have noted that increasing workpiece speed has the effect of reducing the temperatures generated and consequently lower the possibility of thermal damage on the component.[5,6] This is because by allowing the work to rotate as fast as possible the grinding hot-spot spends the least possible time in any given area and so the energy has less time to transfer to the work before the hotspot moves on.

Ultimately, for customers there are only two key quality constraints; Form error and thermal damage, with cycle time as an optimisation that can be mitigated by cost (by adding more machines in parallel).

We propose switching away from calculating a workspeed based on maximising cut depth within multiple hard limits, to a two phase approach each focused on one customer quality constraint.

4.1. Phase one: Maximize part velocity while maintaining form.

No consideration is given at this stage to thermals, wheel wear etc. The focus is solely on axis dynamics constraints: axis speed, acceleration, jerk, and snap. While existing research tends to focus on acceleration and jerk [7], anecdotally these correlate closely with motor mechanics, drive electronics, form error and surface finish respectfully. More research to confirm this is needed.

Back calculating the speed based on the axis dynamics directly is mathematically hard – Jerk requires solving 3rd order integration, and all the limits must be solved as a simultaneous system. Forward calculations however are significantly easier as we are only concerned with movement derivatives. This gives us the opportunity to generate 'proposition' workspeeds and to run the forward calculations and give them a score – the lower the time per revolution the better.

This is an ideal candidate for an AI based solution. Instead of attempting to back-calculate via an extremely complex mathematical problem "absolutely", we apply an Evolutionary Artificial Intelligence technique (EA) to provide a very close estimation and use the forward calculation to 'score' each proposition.

The EA can very rapidly make repeated proposition groups, each better than the last as the AI learns from the score of previous results. The technique is evolutionary as it takes inspiration from the way natural selection promotes successful individuals, and uses them as the basis for future generations.

Eventually, the propositions converge to a solution – this may not be the mathematically perfect optimum and doesn't have to be, just very close and good enough.

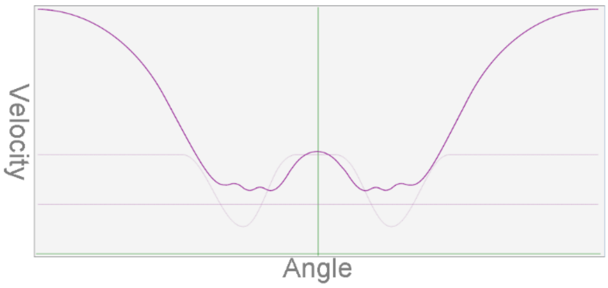

Figure 5. Fully optimised

The result of this phase is a finished workspeed profile which can then be used as the basis for phase 2.

4.2 Phase two: Maximise feed rate while staying within thermal envelope

Now there is a given workspeed profile, the feed rate (cut depth) can be optimized by focusing on only the surface temperature. Other factors will come into play as part of the calculation (MMR, power etc) but we are only concerned about maximising cut depth while not exceeding the thermal limit. While not trivial, this is a straightforward calculation which can be fed a number of cut depths until an optimum is found.

5. Conclusions

This paper has presented a novel two-phase approach to workspeed optimization in high-speed grinding operations for complex workpieces. By reframing the problem around customer quality constraints (form error and thermal damage) and utilizing the power of Evolutionary Artificial Intelligence (EA), the proposed method overcomes the limitations of traditional approaches.

The resulting work-speed and feed parameters can be quite surprising, but also result in a dramatic reduction of feed time. Not only is Jerk significantly reduced but thermal impact too. In a customer case study involving multiple cams on a single shaft, the whole process was improved such that a floor-to -floor time saving of 18% was achieved.

5.1 Key findings:

- Traditional Workspeed limitations: Oversimplification of burn mitigation, counterintuitive effects on burn, and mathematical complexity limit the effectiveness of traditional methods.
- Two-phase optimization: Phase 1 maximizes part velocity while maintaining form through AI-driven workspeed generation, while Phase 2 maximizes feed rate within the thermal envelope.
- Benefits: This approach offers improved:
    - Axis position accuracy for better grinding quality.
    - Minimized damage risk by reducing peak material removal rates.
    - Grinding efficiency and quality through faster operation for certain sections.
    - Machine competitiveness in demanding production environments.

5.2 Future work:

- Validate the proposed approach through experimental testing and comparison with existing methods.
- Investigate the potential of applying the two-phase framework to other advanced machining processes.
- Further explore the application of AI techniques for optimizing machining parameters.

Overall, this paper presents a promising new direction for workspeed optimization in high-speed grinding. By leveraging AI and focusing on customer-centric quality constraints, the proposed method offers significant potential to improve productivity and quality in demanding manufacturing environments. There is also the possibility of artificially suppressing some of the derivative limits to create a sliding scale between targeting productivity or quality.

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