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CNC drilling of wear-resistant Hardox 450 steel using HSSCo solid drills with variable feed rates

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Abstract. Wear-resistant martensitic plates are widely used in agricultural machinery but are difficult to drill during fabrication and repair. This study compared constant-feed and depth-adaptive CNC drilling of 12 mm Hardox 450 using cost-effective 8 mm HSS-Co twist drills under flood cooling. Axial force was recorded in real time using a Kistler piezoelectric dynamometer and interpreted together with repeated-hole behaviour, tool-edge condition, and chip morphology. Under constant-feed drilling at Vc = 20 m min^{-1}, the maximum axial force increased from approximately 980 N in the first hole to 2130 N in the third hole.
Under the depth-adaptive feed condition at the same cutting speed, peak axial force remained at approximately 900–910 N across the three-hole sequence and was associated with a smoother breakthrough response, less visible edge deterioration, and more regular chip morphology. Within the limits of this short-run feasibility study, the results suggest that breakthrough-oriented feed reduction may reduce drilling load and support more stable breakthrough behaviour without changing the tool type or machine platform.

Key words: adaptive feed, agricultural machinery, axial force, drilling, wear plate, wear-resistant steel.

INTRODUCTION

Wear-resistant agricultural machine parts operate in soils, biomass streams, and particle rich environments that accelerate material loss because they extend life under abrasion and impact, while economical hole making remains essential in manufacture and repair (Stephenson & Agapiou, 2016; Emmendorfer et al., 2018; Rojacz et al., 2022). Digital agriculture further links material choice with maintenance planning (Nie et al., 2022).

Hardox 450 combines high hardness with useful toughness, but the same martensitic structure worsens machinability (Emmendorfer et al., 2018; Jiang et al., 2023). Similar studies show that practical performance depends on the hardness–toughness balance rather than hardness alone (Emmendorfer et al., 2018).

In manufacturing terms, drilling therefore becomes a bottleneck operation that can govern dimensional reliability, tool consumption, and the economic viability of repair work on thick wear plate (Stephenson & Agapiou, 2016; Habib et al., 2021). This makes

machining behaviour relevant to serviceability as well as durability (Stephenson & Agapiou, 2016; Emmendorfer et al., 2018). Drilling research on difficult materials continues to show that tool entry and breakthrough are the most sensitive stages because force transients, chip evacuation problems, and sudden loss of support near hole exit can accelerate local edge damage (Stephenson & Agapiou, 2016). Reviews of hard-to-machine alloys emphasize this sensitivity (Machado et al., 2024). Stable force history also matters for surface integrity and functional performance, not only cycle time (Liao et al., 2021; la Monaca et al., 2021). Breakthrough is often the most critical stage because support beneath the chisel edge collapses (Stephenson & Agapiou, 2016).

Recent research therefore emphasizes sensing and monitoring. Smart toolholders and edge analytics connect force signatures with tool state and process stability (Cooper et al., 2024). Reviews describe a shift toward online decision support (Cheng et al., 2022; Kang et al., 2025).

Learning-based monitoring now includes multi-step prediction, generalization, and physics-informed models under variable cutting conditions (Cheng et al., 2022). Related work uses recurrent Gaussian processes and hidden Markov models for wear forecasting (Cheng et al., 2022; Kang et al., 2025).

Such advances are relevant to agricultural engineering because compact sensor systems can deliver actionable drilling information (Nie et al., 2022; Cooper et al., 2024). Their value depends on integration with machining decisions (Kim et al., 2024).

Feed rate is the key controllable variable for chip load, thrust, and heat generation in drilling hard steels (Kıvak et al., 2012; Stephenson & Agapiou, 2016; Machado et al., 2024). Adaptive feed strategies can therefore limit overload without sacrificing the full cycle (Oh et al., 2023; Kim et al., 2024).

Force-constrained CNC studies and advanced hole-making research support the same stage-specific load-management principle (Oh et al., 2023; Kim et al., 2024). Nonconventional drilling studies reach similar conclusions (Kıvak et al., 2012; Wu et al., 2025). Cooling, lubrication, and tool geometry also interact with feed adaptation in hard steels (Kıvak et al., 2012; Stephenson & Agapiou, 2016). Reviews focused on high-strength steel drilling stress this coupled effect (Machado et al., 2024).

Despite rapid progress in monitoring and sustainable machining, experimentally grounded evidence for drilling commercial Hardox 450 plate with economical HSSCo twist drills remains limited under industrial conditions where a depth dependent feed change can be programmed directly on a standard CNC machine (Emmendorfer et al., 2018; Kim et al., 2024). This gap matters in agricultural workshops, where premature tool failure quickly erodes the cost advantage of conventional drills and force-based case studies remain scarce (Emmendorfer et al., 2018; Nie et al., 2022). Specific evidence combining Hardox-type plate, HSS-Co drills, and simple feed adaptation is still limited (Kıvak et al., 2012; Emmendorfer et al., 2018; Kim et al., 2024). Recent machining studies on Hardox steels have likewise shown that cutting conditions strongly influence tool wear, cutting forces, chip formation, and surface quality (Aslan, 2024).

Accordingly, the aim of this research was to examine whether a simple depth-adaptive feed strategy could reduce axial-force peaks and support more stable breakthrough behaviour during CNC drilling of Hardox 450 with economical HSS-Co drills. To achieve this aim, axial force was measured in real time, constant and adaptive feed strategies were compared, and the resulting stability, edge condition, and chip morphology were evaluated. The contribution of this study is the experimental

evaluation of a directly programmable depth-dependent feed strategy under the specific drilling conditions investigated.

MATERIALS AND METHODS

Experimental concept and workpiece material

This was a focused process-validation experiment rather than a full factorial optimization. Constant feed was compared with a depth-adaptive schedule intended to reduce breakthrough overload under otherwise similar industrial conditions.

The workpiece was a 12 mm thick commercial Hardox 450 plate supplied in the delivered condition. Independent chemical and hardness verification were not part of the available experimental campaign, so the material is reported according to its delivered grade designation. The study therefore addresses machining response rather than alloy certification.

All holes were drilled as through-holes without predrilling so that entry and breakthrough transients would remain prominent, consistent with studies that use through-hole tests to interrogate thrust-force sensitivity (Stephenson & Agapiou, 2016; Machado et al., 2024).

Machine tool, drill, cooling, and force measurement

Experiments were performed on a DMU 100 monoBLOCK with a Heidenhain TNC 530 controller. The toolholder was a TENDO hydraulic holder and the tool was a commercial 8 mm HSS-Co twist drill, DIN 338, 135° point angle. Flood cooling with external emulsion and compressed air chip evacuation was used. Spindle speed was 796 rpm, equivalent to 20 m min-1, representing an industrially relevant cutting condition.

Axial force was measured with a Kistler piezoelectric dynamometer system comprising a multichannel charge amplifier Type 5070, a compatible force sensor platform, and Dynoware software. The nominal force range of the measuring system was 5000 N. Only the axial component was evaluated because it directly reflected drilling load and was the most diagnostic signal in the available dataset.

Drilling strategies and evaluation criteria

In the baseline strategy, feed remained constant from entry to breakthrough. In the adaptive strategy the steady-state value was retained through most of the hole and reduced over the final 3 mm to suppress breakthrough overload.

Table 1. Relative feed schedule used in the adaptive drilling strategy

Drilling zone (mm)	Relative feed level (%)	Feed per revolution, mm rev^{-1}	Functional purpose
0–9	100	0.079	Entry stabilization and steady-state cutting
10	89	0.070	Pre-breakthrough control
11	76	0.060	Breakthrough load reduction
12	63	0.050	Exit stabilization

The values reported in Table 1 are feed-per-revolution values expressed in mm rev^{-1} and not controller-specific command values.

The feed per revolution was reduced from 0.079 mm rev^{-1} to 0.070, 0.060, and 0.050 mm rev^{-1} as the drill approached breakthrough. Each drilling condition was repeated for three through holes. Evaluation therefore focused on representative force traces, peak axial force, repeatability of the drilling response across successive holes, audible signs of instability, visible edge condition, and chip morphology.

Data treatment and study limitations

Because the available experiment was designed as an industrial feasibility study with three consecutive holes per drilling condition, the results were interpreted descriptively rather than through inferential statistics. The axial-force component Fz was used for quantitative evaluation. The recorded force signals were filtered using a second-order Butterworth low-pass filter with a cut-off frequency of 10 Hz to reduce high-frequency measurement noise. The maximum axial force was determined from the filtered Fz signal separately for each drilling cycle. Numerical peaks were interpreted together with contextual process evidence, following recent monitoring studies (Cheng et al., 2022; Kang et al., 2025). The present study did not include quantitative surface roughness measurement, burr metrology, or coordinate based hole geometry assessment. The findings therefore represent a short-run industrial drilling study rather than a universal machinability map.

RESULTS AND DISCUSSION

Axial-force response

Figs 1 and 2 illustrate a lower late-stage axial-force response under the adaptive-feed condition.

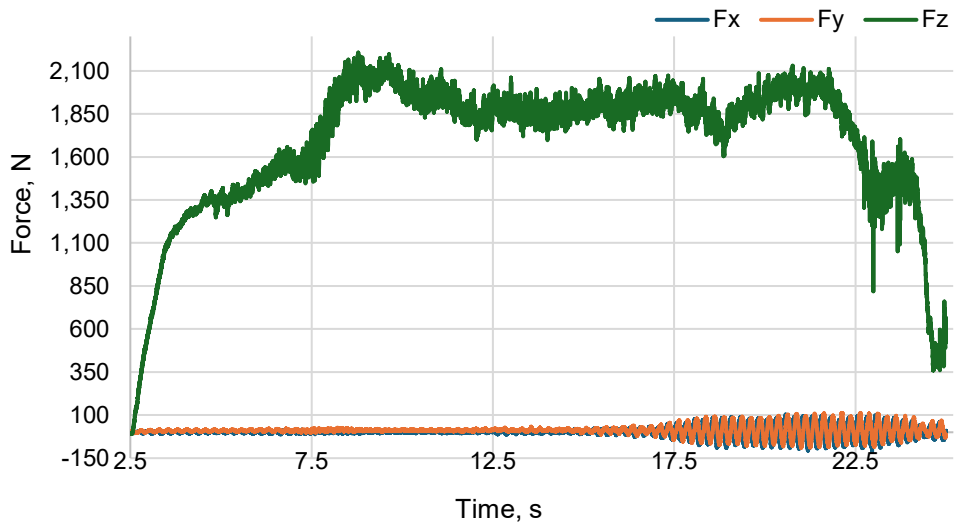


Figure 1. Axial-force response during the third hole under constant-feed drilling of Hardox 450 at Vc = 20 m min^{-1}, showing the increased axial load and dynamic instability.

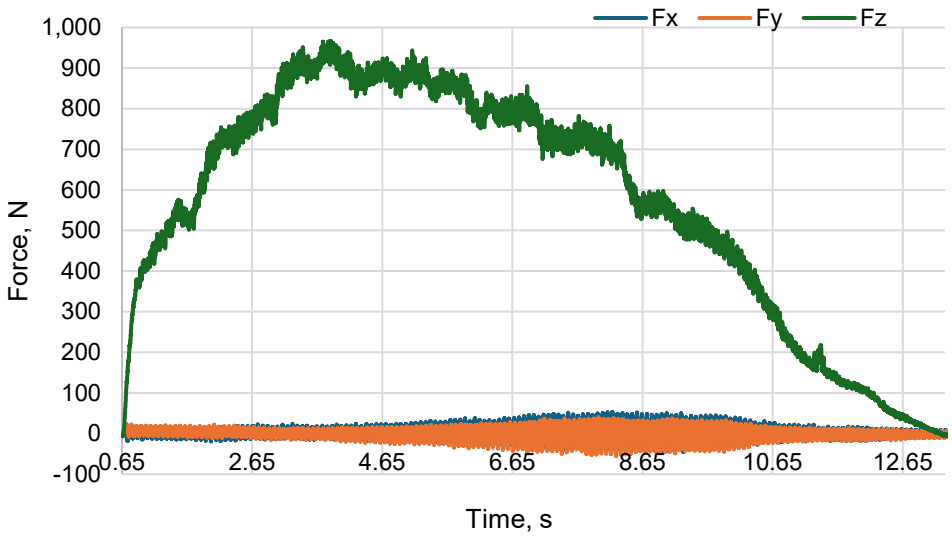


Figure 2. Representative axial-force response during depth-adaptive drilling of Hardox 450 at Vc = 20 m min^{-1}.

Under constant-feed drilling at Vc = 20 m min^{-1}, the maximum axial force increased across the three-hole sequence from approximately 980 N in the first hole to 1450 N in the second hole and 2130 N in the third hole. Under the depth-adaptive feed condition at the same cutting speed, the maximum axial force remained approximately 900–910 N across the three-hole sequence, while the breakthrough response was smoother. The comparison is summarised in Table 2.

Table 2. Axial-force results for the investigated drilling strategies

Drilling strategy	Hole 1	Hole 2	Hole 3
Constant feed, Vc = 20 m min^{-1}	~980 N	~1,450 N	~2,130 N
Depth-adaptive feed, Vc = 20 m min^{-1}	~900 N	~910 N	~910 N

The practical significance of the lower axial-force response lies in the final stage of through-hole drilling, where support under the drill centre decreases and the process becomes more sensitive to force spikes and chip evacuation problems. The constant-feed sequence showed progressive deterioration, with increasing axial force, stronger vibration, and audible instability by the third hole.

Similar escalation of force irregularity before visible failure is reported in recent monitoring studies (Cheng et al., 2022; Kang et al., 2025).

Tool-edge condition

Tool inspection supported the force data. As shown in Figs 3 and 4, after three holes drilled at constant feed, the cutting edge showed visible flank wear, rounding, and local micro chipping, especially near the chisel edge region.

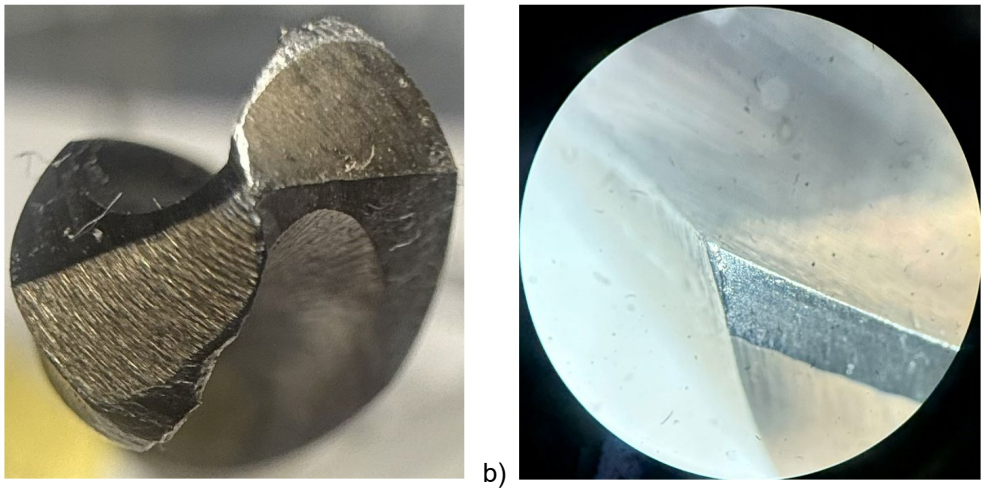


Figure 3. Tool-edge condition after three holes: a) constant-feed drilling, showing edge damage and rounding; b) adaptive-feed drilling, showing less pronounced visible edge deterioration.

After three holes drilled with the variable feed schedule, the cutting edge remained visibly sharper and the wear features were less pronounced. The lower axial-force response was accompanied by less pronounced visible edge deterioration within the tested three-hole sequence. Because no standardized quantitative wear criterion was measured, these observations should be interpreted as qualitative evidence of short-term edge condition rather than as evidence of increased tool life or wear resistance. The damage morphology also matches stress concentration expected in hard martensitic plates. Resistant microstructures can localize damage when contact stress and thermo-mechanical loading concentrate near the cutting edge. Similar local response changes are reported once edge condition deteriorates (Stephenson & Agapiou, 2016; Kang et al., 2025).

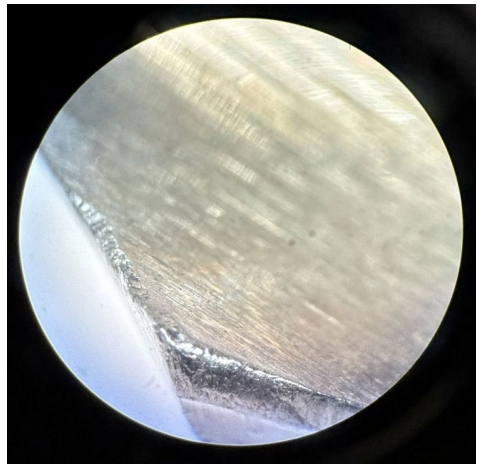


Figure 4. Microscopic view of the worn cutting edge after three holes under constant-feed drilling.

Chip morphology and practical interpretation

Chip morphology provided a third indicator. As shown in Fig. 5, constant feed produced more fragmented breakthrough chips, whereas adaptive feed gave more consistent separation, a pattern associated with lower transient edge overload in HSS and HSS-Co drilling (Kıvak et al., 2012; Stephenson & Agapiou, 2016). The observed sensitivity of the drilling response to the selected cutting strategy is consistent with

previous machining studies on abrasion-resistant steels. Emmendorfer et al. (2018) reported that the machinability of AR450 steel is strongly influenced by machining conditions, while Aslan (2024) showed that process conditions affect machining performance in Hardox 400. Although the machining operations and tool systems differ from the present drilling tests, these studies support the importance of process-parameter control when machining hard martensitic wear-resistant steels.

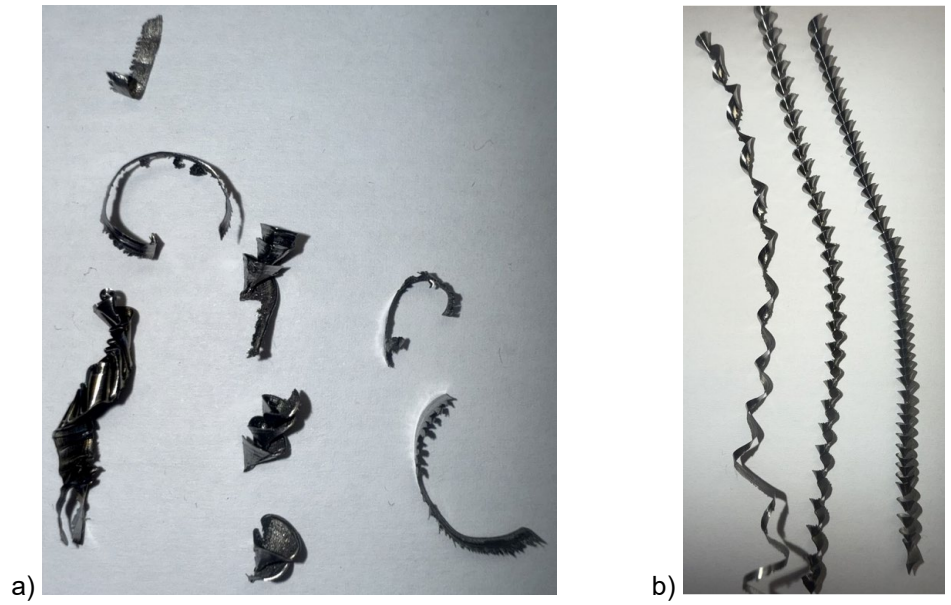


Figure 5. Chip morphology after drilling: a) constant-feed condition with fragmented breakthrough chips; b) adaptive-feed condition with more controlled chip separation.

For the present experiment, the observed chip morphology was consistent with the force and tool-edge observations, with more regular chip formation under the adaptive-feed condition. This stage-selective logic is central to modern adaptive control (Oh et al., 2023; Kim et al., 2024). For small batch manufacturing and repair of wear resistant machinery parts, such a modification can be implemented immediately in CNC code without investment in new tooling or additional hardware. Broader reviews likewise suggest that process adaptation becomes more beneficial as hardness, heat generation, and chip-flow difficulty increase (Machado et al., 2024).

Study limitations and future work

The main limitation of this study is the small experimental dataset, with only three drilled holes evaluated per condition and no inferential statistical analysis. The findings should therefore be interpreted as preliminary observations from a short-run feasibility study rather than as statistically validated evidence of improved tool life, wear resistance, or general process stability.

Future work should add longer tool-life trials, multi-sensor monitoring, hole-quality measurement, and comparison with coated carbide drills. Data-driven wear modelling could convert the present empirical schedule into a more general digital assistant. Economic comparison between tool materials should also be added.

CONCLUSIONS

Under the specific conditions investigated, pronounced changes in axial-force behaviour were observed during breakthrough when drilling 12 mm Hardox 450 with an 8 mm HSS-Co drill.

Under constant-feed drilling at $Vc = 20\ m\ min^{-1}$, the maximum axial force increased from approximately 980 N in the first hole to 1,450 N in the second hole and 2,130 N in the third hole.

A variable feed schedule that preserved the baseline feed from 0–9 mm and reduced the feed during the final 3 mm maintained peak axial force at approximately 900–910 N across the three-hole sequence and produced a smoother exit response. Archived tool-edge and chip images indicated less pronounced short-run edge deterioration and more regular chip morphology under the variable-feed strategy.

For wear-loaded agricultural components, these findings provide a practical indication of the potential value of depth-adaptive feed programming under the tested conditions. Within the limits of this short-run feasibility study, the observed trends support further investigation of depth-adaptive feed programming for Hardox 450 drilling with HSS-Co tooling. Longer campaigns with quantitative hole metrology and full tool wear measurement are still required before broad industrial generalisation can be made.

DECLARATION OF AI USE.During manuscript preparation, the authors used ChatGPT (OpenAI) to improve the English language, reorganize the draft text, and support literature screening. All AI-generated output was critically reviewed and edited by the authors, who take full responsibility for the final content of the manuscript.

Data availability statement. The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

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