

Experimental Investigation of Thermofriction Milling with Pulsed Cooling for Improving the Machinability of Hadfield Steel

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Abstract. Hadfield steel is widely used for components subjected to severe impact and abrasive wear; however, its pronounced work-hardening behavior significantly complicates conventional machining. This study experimentally investigates thermofriction milling with pulsed cooling as an alternative approach for machining 110G13L Hadfield steel. The experiments were conducted using a specially designed friction cutter with a diameter of 250 mm. The investigated machining parameters included spindle speeds of 500–2000 rpm, feed rates of 40–600 mm/min, and depths of cut of 1–5 mm. Surface roughness and hardness were evaluated to characterize the effect of the machining parameters on the resulting surface condition. The results showed that increasing spindle speed reduced surface roughness, whereas increasing feed rate increased roughness. Under favorable machining conditions, a surface roughness of ($R_z \leq 10$) μm was achieved. Surface hardness increased with both spindle speed and feed rate, indicating intensive thermomechanical modification of the machined layer. The experiments confirmed the feasibility of thermofriction milling with pulsed cooling for processing Hadfield steel while also revealing limitations related to surface quality and chip fragmentation. The obtained results provide an experimental basis for the further development of a combined machining method integrating thermofrictional and conventional cutting mechanisms.

Keywords: hadfield steel, 110G13L steel, thermofriction milling, pulsed cooling, difficult-to-machine materials, surface roughness, surface hardness, work hardening

Introduction

Hadfield steel is a high-manganese austenitic steel widely used for components operating under severe impact and abrasive wear conditions. Its combination of high toughness, ductility, and pronounced work-hardening capability makes it particularly suitable for mining, crushing, railway, and heavy engineering applications. Under mechanical loading, plastic deformation of the surface layer can substantially increase its hardness, thereby providing high resistance to wear while retaining a comparatively tough core. Recent investigations continue to confirm that the performance of Hadfield steel is closely associated with the evolution of its surface and subsurface structure during deformation and the resulting work-hardening behavior [1, 2].

However, the same mechanisms that provide Hadfield steel with excellent service properties significantly complicate its machining. Intensive strain hardening occurs directly in the cutting zone, where severe plastic deformation continuously modifies the material ahead of and beneath the cutting edge. Consequently, the cutting tool interacts not only with the initially relatively soft austenitic structure but also with a locally hardened surface layer. This phenomenon results in increased mechanical and thermal loading of the cutting edge, promotes flank and rake-face wear, and can ultimately cause premature chipping or fracture of the cutting insert. The poor machinability of high-manganese steels has therefore remained an important technological limitation in the manufacture and repair of wear-resistant components [3].

For the 110G13L grade investigated in the present study, this problem is particularly relevant. In the initial condition after heat treatment, the material has an austenitic structure and a hardness of approximately HB 260–300. Under dynamic loading and cold deformation, however, its surface hardness may increase considerably, reaching values of up to approximately HB 600. Such behavior makes conventional cutting difficult and results in high consumption of cutting tools. Industrial observations presented in the underlying experimental study demonstrate severe wear, edge chipping, and failure of commercial cutting inserts during machining of 110G13L steel.

Previous investigations into the conventional machining of Hadfield steel have therefore focused largely on the selection of cutting-tool materials and optimization of process parameters. Ceramic and coated carbide tools have been investigated to improve tool life and surface quality. In hard turning, for example, machinability has been evaluated in terms of flank wear and surface roughness as functions of cutting speed, feed rate, depth of cut, and tool geometry [4]. In milling, experimental optimization using PVD- and CVD-coated carbide inserts demonstrated that feed rate strongly influences surface roughness, whereas cutting speed has a major influence on flank wear [5]. These findings illustrate that improvements can be obtained by selecting appropriate cutting conditions; nevertheless, conventional machining still requires the cutting edge to withstand the severe thermomechanical conditions generated during deformation of the work-hardened material.

This challenge has stimulated growing interest in assisted and hybrid machining processes for difficult-to-machine materials. Instead of relying exclusively on the mechanical action of the cutting edge, these approaches introduce an additional energy field or modify the thermal and tribological conditions in the cutting zone. Thermal-, vibration-, laser-, plasma-, and other field-assisted processes have been investigated as means of reducing cutting resistance, controlling material removal mechanisms, improving surface integrity, and increasing machining efficiency. Recent reviews identify field-assisted machining as an important direction for overcoming the inherent limitations of conventional processing of difficult-to-machine materials [6, 7].

Among these approaches, thermally assisted machining is particularly attractive because controlled heating can alter the local mechanical response of the workpiece immediately before or during material removal. The underlying concept is to decrease the resistance of the material in the cutting region while maintaining acceptable properties in the bulk workpiece. Studies of thermally assisted machining have demonstrated that the interaction between heat input and machining parameters can affect cutting forces, cutting-zone temperature, chip formation, tool loading, and the resulting surface condition [8]. At the same time, thermal assistance requires careful control because excessive or uncontrolled heat can adversely affect dimensional accuracy, tool behavior, and surface integrity.

Cooling conditions constitute another important factor in the machining of difficult-to-cut materials. Conventional flood cooling, minimum-quantity lubrication, cryogenic cooling, and high-pressure cooling have all been investigated as methods for controlling heat generation and tool wear. Their effectiveness, however, strongly depends on the combination of workpiece material, cutting conditions, and dominant wear mechanisms. A recent comprehensive review emphasized that no single cooling strategy is universally optimal and that cooling conditions should be selected in accordance with the specific material–process interaction [9]. This suggests that controlled alternation between localized heating and cooling may provide an alternative route for modifying the conditions of material removal.

Thermofriction processing represents a distinctive approach in this context because heat is generated directly through frictional interaction between a rotating tool and the workpiece. In contrast to processes requiring an external laser, plasma, or induction heat source, the mechanical interaction itself produces localized thermal energy. Previous work on thermofriction cutting demonstrated the feasibility of combining friction-generated heating with pulsed cooling [10]. In the experimental configuration considered in the present study, a specially designed friction milling cutter contains alternating functional regions that generate a cyclic thermomechanical effect on the workpiece surface. The original experimental system used a friction cutter with an outer diameter of 250 mm, a heating-zone length of $L_1=24$ mm, a cooling-zone length of $L_2=8$ mm, and a corresponding pitch of $L=32$ mm.

Despite the potential advantages of such a process, the application of thermofriction milling with pulsed cooling to Hadfield steel remains insufficiently investigated. In particular, the relationship between the main machining parameters and the resulting surface condition requires experimental clarification. Surface roughness is essential for the functional performance of machined components, while the hardness of the machined layer provides an indirect indication of the thermomechanical transformations occurring during processing. For Hadfield steel, these characteristics are especially important because the material exhibits a pronounced sensitivity to deformation-induced hardening. Recent studies continue to demonstrate the strong relationship between deformation, structural evolution, and surface hardness in Hadfield steels [1, 2].

Thermofrictional processing represents another approach to the machining of difficult-to-machine materials, in which the heat generated by intensive frictional interaction is utilized to modify the material conditions in the machining zone. Previous studies demonstrated the feasibility of thermofrictional cutting with pulsed cooling and showed that periodic thermal action can be incorporated into the material removal process [13]. The approach was further developed for thermal friction turn-milling of high-strength materials, where its influence on surface quality, hardness, and chip formation was experimentally investigated [14]. Subsequent experiments extended thermofrictional milling with pulsed cooling to 110G13L Hadfield steel and confirmed the possibility of machining this highly work-hardening material using friction-induced heating combined with periodic cooling [15]. In parallel, investigations into the geometry of thermofriction cutting tools [16] and the development of a dedicated disk cutter for thermofriction cutting with pulsed cooling [17, 18] provided the technological basis for further improvement of the process.

The preliminary experiments forming the basis of the present investigation demonstrated that thermofriction milling with pulsed cooling can be implemented for 110G13L steel. The experiments were conducted over spindle speeds of 500–2000 rpm, feed rates of 40–600 mm/min, and depths of cut of 1–5 mm. Surface roughness and hardness were subsequently evaluated using TR100 and TKM 459M measuring instruments, respectively. These observations provide an experimental basis for determining how variations in machining conditions influence the surface generated by thermofriction milling.

Accordingly, the aim of this study is to experimentally investigate the feasibility and process characteristics of thermofriction milling with pulsed cooling during the machining of 110G13L Hadfield steel and to evaluate the influence of machining parameters on the resulting surface roughness and hardness. Particular attention is paid to the effects of spindle speed and feed rate and to the technological limitations associated with surface quality and chip formation. The novelty of the study lies in the experimental evaluation of a thermofriction milling process in which

friction-induced localized heating is combined with pulsed cooling for the machining of high-manganese Hadfield steel. The obtained results are intended to establish an experimental basis for the subsequent development of a combined machining approach integrating thermofrictional and conventional cutting mechanisms.

1. Materials and Methods

1.1 Workpiece Material

The experimental investigation was carried out using high-manganese austenitic Hadfield steel, designated as 110G13L. This material is widely used for components operating under severe impact and abrasive wear conditions owing to its high toughness and pronounced work-hardening capability.

The workpieces used in the experiments were specimens cut from an armor plate of an ore-receiving hopper manufactured from 110G13L steel. The initial hardness of the workpiece material was within the range of HB 260–300 (approximately HRC 27–33).

A characteristic feature of 110G13L steel is its strong tendency to strain hardening. Although the material possesses a predominantly austenitic structure and relatively moderate hardness in its initial condition, severe plastic deformation can considerably increase the hardness of the surface layer. This behavior is one of the principal factors responsible for the poor machinability of Hadfield steel and imposes high mechanical and thermal loads on conventional cutting tools.

For the present investigation, thermofriction milling with pulsed cooling was selected as an alternative material-removal approach. The method utilizes friction-induced heat generated through the interaction between a rapidly rotating friction cutter and the workpiece surface, while periodic cooling modifies the thermal conditions in the contact zone.

1.2 Experimental Setup

Experimental thermofriction milling was performed on a BM-127M vertical knee-type milling machine. The 110G13L steel specimen was rigidly fixed on the machine table using a dedicated fixture to provide stable positioning during processing. A specially designed friction cutter was mounted in the machine spindle and rotated at the prescribed spindle speed.

The experimental arrangement consisted of the workpiece, clamping fixture, rotating friction cutter, and a cooling-fluid supply system. During machining, frictional interaction between the rotating cutter and the workpiece generated localized heating in the contact region. Pulsed cooling was applied through a supply tube directed toward the processing zone.

The original experiments visually demonstrated intensive interaction between the friction cutter and the workpiece, accompanied by material removal and chip formation. The photographs of the process also showed the condition of the machined specimens and the chips obtained after thermofriction milling.

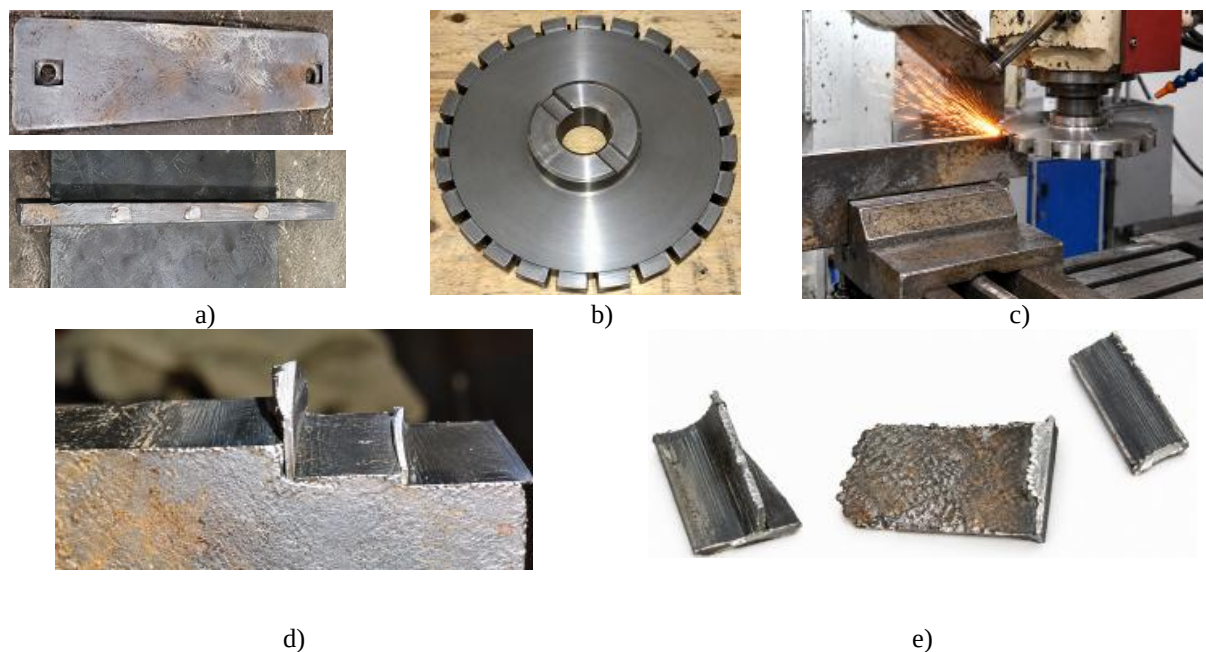


Fig. 1 – Experimental setup and thermofriction milling of 110G13L Hadfield steel with pulsed cooling: (a) workpiece specimen; (b) friction cutter; (c) experimental machining process; (d) machined surface; (e) chips produced during thermofriction milling

1.3 Design and Geometrical Parameters of the Friction Cutter

A specially designed friction cutter manufactured from 45 steel was used for the experiments. The cutter had an outer diameter of 250 mm and incorporated alternating heating and cooling regions along its circumference. The geometry of the cutter was selected according to the thermofriction processing concept developed in previous studies.

The principal geometrical parameters were:

$$D=250 \text{ mm},$$

$$L_1=24 \text{ mm},$$

$$L_2=8 \text{ mm},$$

$$L=L_1+L_2=32 \text{ mm},$$

where (D) is the outer diameter of the friction cutter, (L_1) is the length of the heating zone, (L_2) is the length of the cooling zone, and (L) is the circumferential pitch of the functional regions. These dimensions correspond to those reported for the experimental cutter in the original study.

During cutter rotation, the heating region periodically interacted with the workpiece and generated heat as a result of friction and plastic deformation. The subsequent cooling region enabled the cutting zone to be exposed to the supplied cooling medium. Thus, successive cutter rotations produced cyclic heating and cooling of the workpiece surface.

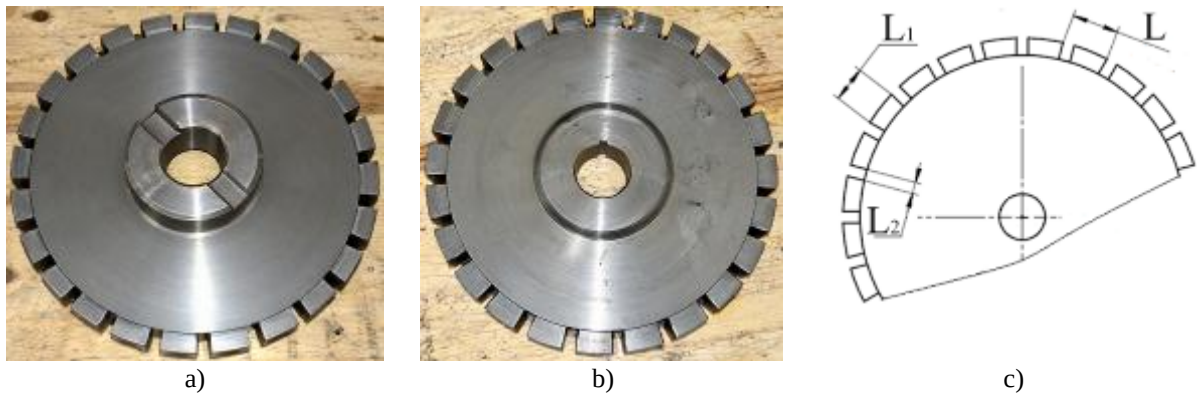


Fig. 2 – Friction cutter used for thermofriction milling with pulsed cooling: (a) general view; (b) bottom view; (c) schematic representation of the cutter geometry; L_1 — heating zone; L_2 — cooling zone; L — circumferential pitch.

1.4 Machining Parameters

The experimental investigation was conducted by varying the principal thermofriction milling parameters over the ranges specified in Table 1. Three process variables were considered: spindle speed (n), feed rate (S), and depth of cut (t).

Table 1. Experimental matrix and processing parameters for thermofriction milling

Process parameter	Symbol	Range	Unit
Spindle speed	n	500, 1000, 2000	rpm
Feed rate	S	40, 200, 600	mm/min
Depth of cut	t	1, 3, 5	mm

These ranges correspond to the experimental conditions reported for thermofriction milling of the investigated 110G13L specimens.

The principal responses used to assess the machining performance were the surface roughness and hardness of the machined surface. Accordingly, the experimental relationships can be generally represented as

$$R_z=f(n,S,t),$$

and

$$HB=f(n,S,t),$$

where (Rz) is the surface roughness parameter and (HB) is the hardness of the machined surface.

The selected ranges were intended to determine the general influence of the thermofriction milling conditions on the quality of the machined surface and to identify processing conditions capable of producing an acceptable surface condition.

1.5 Pulsed Cooling during Thermofriction Milling

Pulsed cooling was applied directly to the interaction zone between the friction cutter and the workpiece. The cooling medium was supplied through a tube positioned near the machining region, as illustrated in Figure 1.

The configuration of the friction cutter produced alternating thermal conditions during processing. When the heating section of the rotating cutter contacted the workpiece, frictional interaction generated localized heat. The subsequent passage of the cooling section provided an interval during which cooling fluid could act on the heated region. This sequence was repeated cyclically during cutter rotation.

Consequently, unlike continuous conventional milling, the investigated process involved a repeated frictional heating–pulsed cooling cycle. This cyclic thermomechanical action constitutes the principal technological feature of the investigated thermofriction milling method.

1.6 Surface Roughness and Hardness Measurements

The quality of the machined surface was evaluated using two principal indicators: surface roughness and hardness.

Surface roughness was measured using a TR100 portable surface roughness tester. The measurements were performed on the surfaces obtained after thermofriction milling under different machining conditions. The roughness parameter (Rz) was used to characterize the surface condition.

The hardness of the machined surface was evaluated using a TKM 459M portable hardness tester. The instrument was used to determine changes in surface hardness associated with variations in the thermofriction milling parameters.

Both instruments used in the experimental investigation are shown in Figure 3.

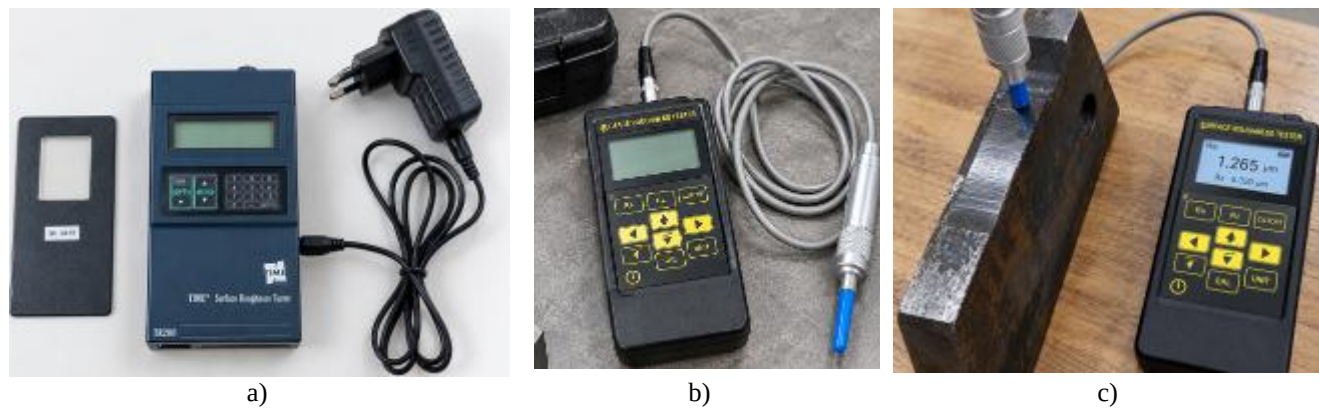


Fig. 3 – Instruments used for evaluating the quality of the machined surface: (a) TR100 surface roughness tester; (b) TKM 459M hardness tester; (c) hardness measurement of the machined 110G13L steel specimen.

The use of these instruments and their purpose are explicitly reported in the original experimental methodology.

The obtained measurements were subsequently used to determine the influence of spindle speed and feed rate on the surface condition of Hadfield steel. Particular attention was given to identifying the tendencies of (Rz) and surface hardness with increasing process intensity.

1.7 Experimental Evaluation Procedure

The overall experimental procedure consisted of the following sequence:

- preparation and rigid fixation of the 110G13L steel specimen on the milling machine;
- installation of the specially designed Ø250 mm friction cutter;
- setting of the required spindle speed, feed rate, and depth of cut;
- thermofriction milling of the workpiece with pulsed cooling;
- examination of the resulting machined surface and chip formation;
- measurement of the surface roughness using the TR100 instrument;
- measurement of the surface hardness using the TKM 459M instrument; and
- analysis of the relationships between the machining parameters and the resulting surface-quality indicators.

The experimental methodology was therefore designed to evaluate both the feasibility of thermofriction milling with pulsed cooling for 110G13L Hadfield steel and the influence of the principal process parameters on the resulting surface characteristics.

2. Results and Discussion

2.1 Experimental Evaluation of the Thermofriction Milling Process

The experimental results confirmed the feasibility of thermofriction milling with pulsed cooling for machining 110G13L Hadfield steel. During processing, frictional interaction between the rotating cutter and the workpiece resulted in localized thermomechanical action followed by periodic cooling of the interaction zone. Material removal and chip formation were observed throughout the experiments.

Representative thermofriction milling processes, machined specimens, and the resulting chips are shown in Figure 1.

The experiments demonstrated that the investigated method can be applied to austenitic high-manganese steel despite its pronounced work-hardening tendency. However, the experiments also revealed limitations associated with surface quality and chip fragmentation.

2.2 Influence of Machining Parameters on Surface Quality

The experimental results showed that the surface condition was strongly affected by the thermofriction milling parameters. An increase in spindle speed resulted in a reduction in surface roughness, whereas increasing the feed rate led to higher roughness values.

The improvement in surface quality at higher spindle speeds can be associated with more intensive frictional interaction and localized heat generation in the tool–workpiece contact region. Under these conditions, the thermomechanical state of the surface layer is modified, which may facilitate material removal and promote the formation of a more uniform machined surface. In contrast, increasing the feed rate reduces the interaction time per unit length of the workpiece and intensifies mechanical loading, resulting in deterioration of the surface finish.

Under the favorable machining conditions investigated in this study, a surface roughness of $R_z \leq 10 \mu\text{m}$ was achieved, indicating that the resulting surface quality is suitable for the investigated wear-resistant Hadfield steel components.

This result confirms the potential of thermofriction milling with pulsed cooling for processing Hadfield steel. Nevertheless, the achieved roughness also indicates that further improvement of the process is required when higher surface-quality requirements are imposed.

2.3 Surface Hardness and Technological Limitations

The hardness of the machined surface increased consistently with increasing spindle speed and feed rate. This behavior is consistent with the pronounced work-hardening capability of Hadfield steel and indicates that the surface layer experiences intensive mechanical and thermal loading during thermofriction milling.

The simultaneous decrease in surface roughness and increase in hardness with increasing spindle speed is particularly important. It indicates that spindle speed affects not only the geometrical quality of the machined surface but also the mechanical condition of its surface layer. However, the present measurements are insufficient to determine the underlying microstructural transformations, and further metallographic and microhardness investigations would be required.

Although the experiments confirmed the feasibility of the proposed method, two technological issues remained unresolved: obtaining a higher-quality finished surface and ensuring effective chip fragmentation. These limitations provide a basis for the further development of a combined machining method integrating thermofrictional action with conventional cutting, as proposed in the underlying study.

Conclusions

The experimental investigation of thermofriction milling with pulsed cooling for machining 110G13L Hadfield steel led to the following conclusions:

1. Thermofriction milling with pulsed cooling is feasible for machining 110G13L Hadfield steel. The experiments demonstrated stable material removal and chip formation despite the pronounced work-hardening tendency and poor machinability of the investigated material.
2. Surface roughness (R_z) was directly influenced by the thermofriction milling parameters. Increasing the spindle speed resulted in a decrease in surface roughness and improved the surface finish, whereas increasing the feed rate led to higher roughness values and deterioration of the surface finish. Under favorable machining conditions, a surface roughness of $R_z \leq 10 \mu\text{m}$ was achieved.
3. The hardness of the machined surface increased with increasing spindle speed and feed rate. This behavior indicates intensive thermomechanical interaction between the friction cutter and the surface layer of Hadfield steel during processing.

4. Although the investigated method demonstrated its potential for machining Hadfield steel, surface quality and effective chip fragmentation remain the main technological limitations of standalone thermofriction milling with pulsed cooling.

5. The obtained results provide an experimental basis for the further development of a combined machining method integrating thermofrictional and conventional cutting mechanisms. Such an approach is expected to utilize thermofrictional action to modify the material condition prior to conventional material removal, with further research required to evaluate its effects on surface quality, chip formation, tool life, and machining productivity.

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