

Assessment of the Potential of CO₂ as a Lubricant in Cold Forging of Low-Carbon Mild Steel

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Abstract. Lubrication plays a crucial role in cold forging, influencing key factors such as material flow, surface quality and tool wear. The current state of the art presents conventional mineral-oil-based lubricants as one of a range of effective solutions; however, they generate residues, require cleaning and pose environmental concerns. This work explores CO₂ snow as a potential residue-free, sustainable alternative for cold forming of mild steels. Miniature spike tests were conducted to characterise friction behaviour under varying lubrication and surface conditions. The study demonstrates that CO₂ snow can effectively reduce friction, promote favourable material flow and achieve surface finishes comparable to conventional oils, while eliminating residue and post-processing requirements. These findings suggest that CO₂ snow represents a promising eco-friendly lubrication strategy, offering both technical performance and environmental benefits for sustainable cold forging operations.

Introduction

Cold forging of steels traditionally relies on phosphated semi-finished products in combination with mineral oil- or soap-based lubricants to ensure effective separation between tool and workpiece [1, 2]. While these conventional lubrication systems provide reliable technical performance, they are exposed to ecological and economic challenges. It is estimated that 40–50% of 5 million tons of lubricants being used annually in the EU are ultimately released into the environment [3, 4].

The increasing demand for green and sustainable manufacturing has raised environmental concerns associated with the usage and disposal of oils. Particularly, their inherent toxicity and non-biodegradability have brought forth significant environmental problems [5, 6]. For instance, mineral-oil-based lubricants in metal forming and machining have been associated with the generation of oil mist and aerosol emissions during processing, which accumulate on tools and workpieces and often require subsequent cleaning or filtration steps to avoid contamination and ensure workplace safety [7, 8]. Collectively, these factors represent a substantial sustainability challenge in modern cold forging processes.

To overcome such challenges, alternative lubrication strategies are being explored, among which the use of CO₂ snow as a residue-free lubricant shows particular promise. CO₂ snow is already employed industrially for precision cleaning and utilizes CO₂ that is generally a byproduct of other chemical processes, avoiding additional greenhouse gas emissions [9]. Its key advantage in metal forming lies in its ability to evaporate completely after processing, eliminating cleaning and disposal steps, reducing water and chemical usage, and improving both ecological and economic efficiency [10]. By removing the environmental and operational burdens of conventional lubricants, CO₂ snow could enable a step change in sustainable cold forming technology. While CO₂ snow has been successfully applied in sheet metal forming [7, 10], its potential in bulk forming remains largely unexplored. On the context of sheet metal forming, liquid CO₂ proved to be the most effective volatile lubricant for dry deep drawing, providing the lowest friction and wear among all tested media due to dry ice formation and surface cooling. In addition, CO₂ offered a cleaning effect, improved process stability, and the potential to replace conventional oil-based lubricants, enhancing both environmental sustainability and economic efficiency [11].

Although the environmental and operational benefits of residue-free CO₂ snow are clear, a critical challenge remains accurately evaluating its lubrication performance under realistic cold forging conditions. Friction directly influences material flow, tool wear and forming forces, making sensitive tribological characterisation essential. In this context, the spike test, developed by Isogawa, has emerged as a widely used method for this purpose [12]. In the spike test, a cylindrical billet with a centring pin is formed into a spike through combined upsetting and extrusion, producing a central extruded pin, a conical section with an opening angle of 6°, and an upsetting zone approximated by a cone with an opening angle of 174° [13]. Small, wave-shaped grooves on the punch surface help control material flow during forming. A schematic representation of the spike test is shown in Fig. 1a. For such tests, force–displacement curves typically show an initial steep rise, a nearly linear region, and a final sharp increase as the contact area expands [14], as depicted in Fig. 1b. Several studies confirm that the spike test is an effective method for assessing lubrication performance in cold forging and enables the investigation of cold welding phenomena and optimising forming conditions under varying frictional scenarios [15–18].

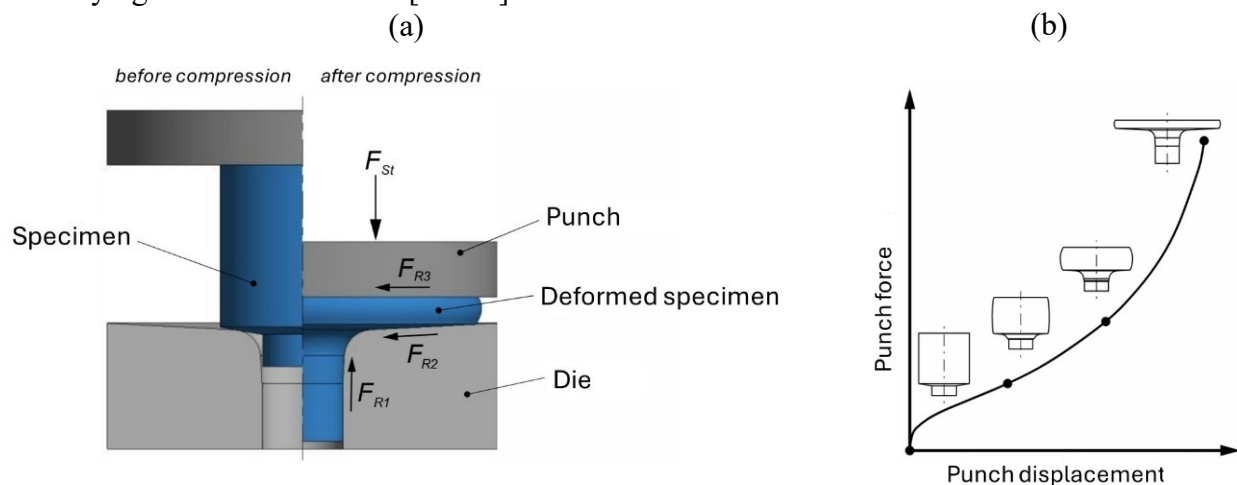


Fig. 1. (a) Schematic illustration of the spike test [19]; (b) typical force–displacement curve obtained from the test [14].

The objective of this investigation is to systematically evaluate the performance of CO₂ snow in the cold forging of steels and to quantify its effect on friction under realistic process conditions. The results enable an assessment of CO₂ snow as a potential sustainable, residue-free lubrication strategy for cold forging applications. This is achieved through an experimental approach employing the miniature spike test for friction characterization. Experiments are conducted on mild steel specimens under various lubrication and surface conditions, allowing the derivation of force–displacement responses as well as geometric changes of the specimens. Based on this methodology, the study provides a quantitative comparison between CO₂ snow and conventional lubricants and establishes a framework for evaluating residue-free lubrication concepts in cold forging processes.

Experimental Procedure

The friction characterisation was carried out using the miniature spike test, selected due to its high sensitivity to interfacial friction conditions in bulk metal forming [19]. The specimen geometry is shown in Fig. 2a and die geometry used in this study is shown in Fig. 2b. A modified version of the original die geometry developed by Isogawa [12] was adopted in this study. The scale of the experiment was adjusted because the diameter of the raw material used in the intended industrial process was insufficient for the original spike test setup.

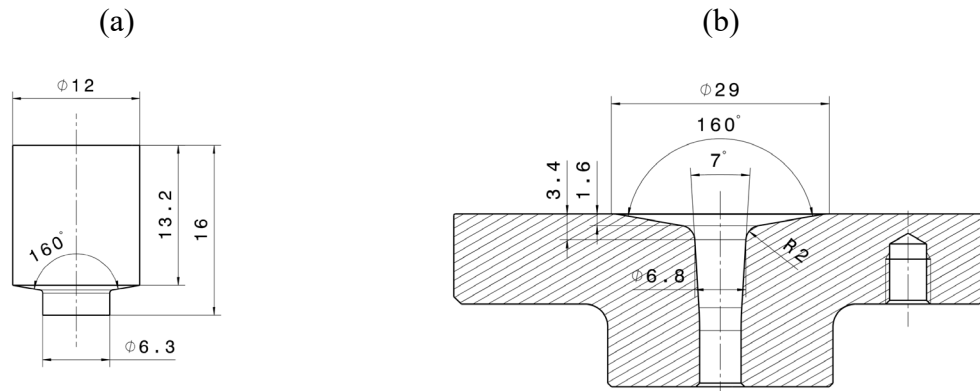


Fig. 2. (a) Geometry of the miniature spike test specimen; (b) geometry of the miniature spike test die.

The workpiece material was a standard mild steel, C15E, supplied as bar material and subsequently machined into the required miniature spike geometry. Three lubrication conditions were investigated, namely CO₂ snow, a conventional oil for cold forging and a non-lubricated condition. The influence of a surface preparation was also considered with different initial surface roughness conditions being addressed. To generate different surface conditions, the specimens were shot-blasted under three different pressure levels, while the unblasted surface served as the reference state. Spheric glass particles with a diameter of about 100 μm were used as shot blasting material. Table 1 summarises the different parameter combinations examined in the experimental campaign. For each condition three samples were tested and the results were averaged.

Table 1. Summary of the distinct parameter sets examined as part of this study.

Group	Lubricant	Shot blasting pressure level [bar]	Initial Roughness Sa [μm]
1	CO ₂	8	1.93
2	CO ₂	5.5	1.71
3	CO ₂	3	1.28
4	CO ₂	Unblasted	0.93
5	Reference Oil	8	1.93
6	Reference Oil	5.5	1.71
7	Reference Oil	3	1.28
8	Reference Oil	Unblasted	0.93
9	Dry - No lubricant	8	1.93
10	Dry - No lubricant	5.5	1.71
11	Dry - No lubricant	3	1.28
12	Dry - No lubricant	Unblasted	0.93

The experiments were performed on a hydraulic press with a maximum capacity of 2,000 kN. A load cell and displacement sensor integrated into the press machine were used to acquire force–displacement curves during deformation. The experimental setup is depicted in Fig. 3.

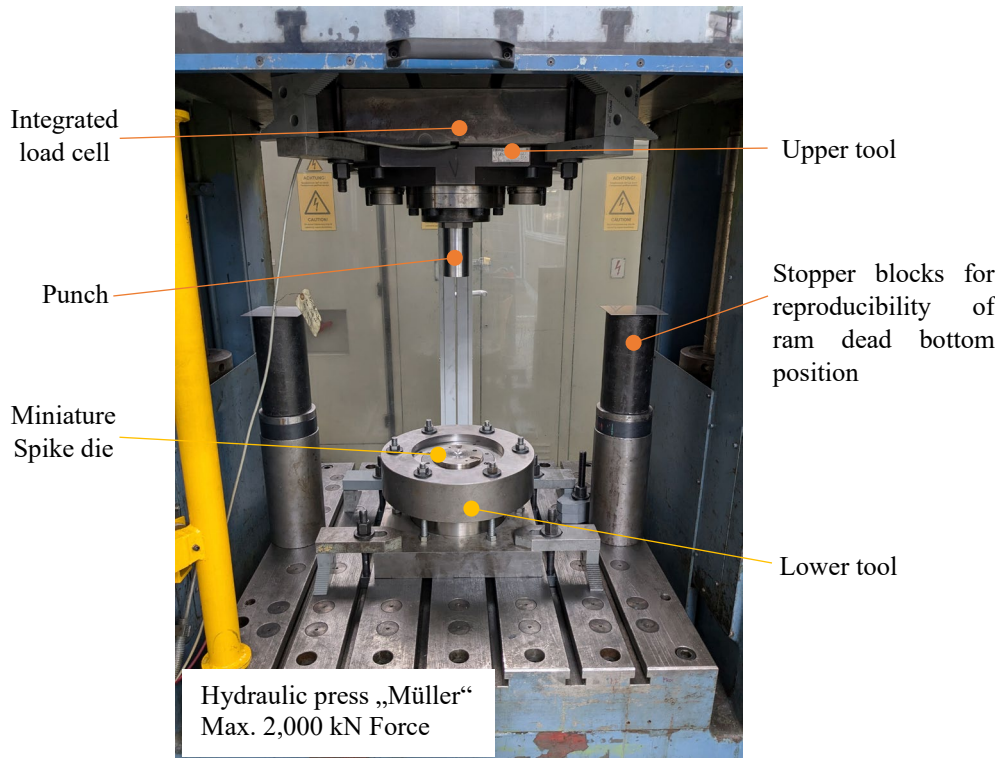


Fig. 3. Experimental setup for the miniature spike test.

CO₂ snow was applied in a sequential step to ensure full and repeatable coverage of both the die and the specimen surface. The CO₂ application sequence is shown in Fig. 4: first CO₂ snow was deposited on the die (Fig. 4a), then the specimen was positioned using a centring specimen holder (Fig. 4b), and finally CO₂ snow was applied on the specimen itself before upsetting (Fig. 4c).

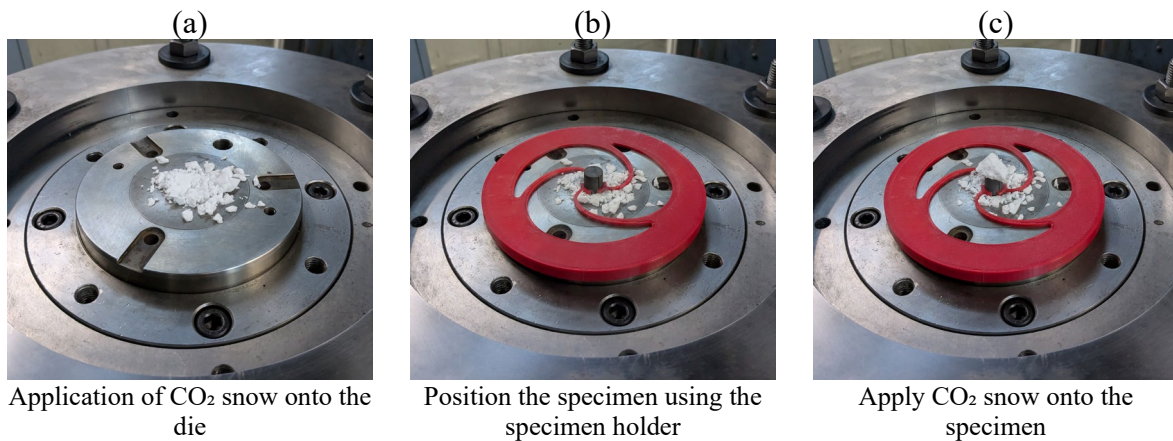


Fig. 4. Step-by-step procedure for applying CO₂ snow to the specimens' relevant surfaces.

For optical roughness measurements, a μ -Surf confocal microscope from NanoFocus was used. The measurement setup is illustrated in Fig. 5a while Fig. 5b illustrates the regions selected for surface measurement before and after the experiment.

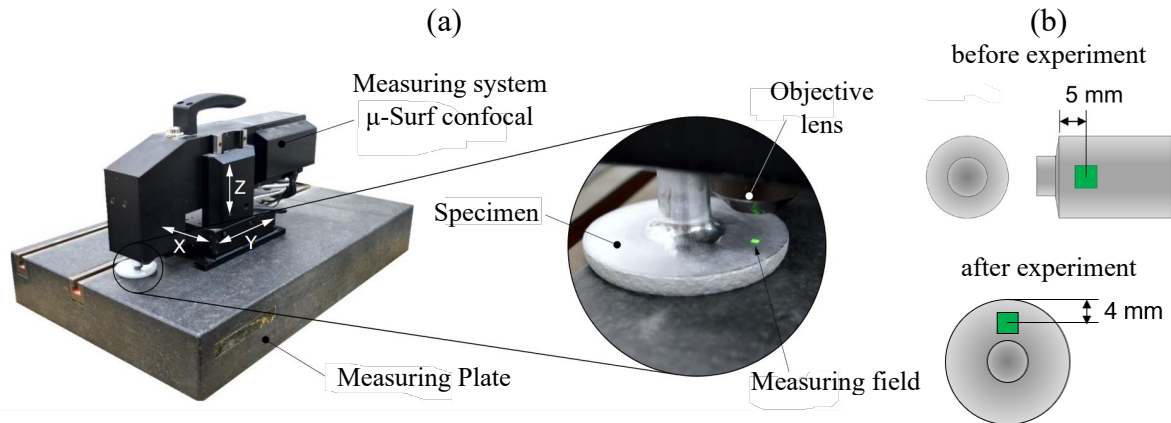


Fig. 5. (a) Confocal microscopy for optical surface roughness measurement and detailed view of the measured area [19]; (b) measurement positions on the specimen surface before and after the experiment.

Results & Discussions

The force–displacement curves obtained from the experiments for the three lubrication conditions at an initial surface roughness of $S_a = 1.93 \mu\text{m}$ are shown in Fig. 6a, and the corresponding averaged maximum forces for all parameter sets are summarised in Fig. 6b. As expected, the overall trend indicates that sample group 9-12 (dry condition) exhibited the highest peak forces, reaching up to 342.52 kN for Group 12.

In contrast, sample group 5-8 (mineral oil lubrication) recorded the lowest average maximum forces, with the lowest maximum force of 288.98 kN for Group 7. Together with the final geometrical measurements, the force–displacement response provides valuable insights into the lubrication performance and the forming behaviour of each sample.

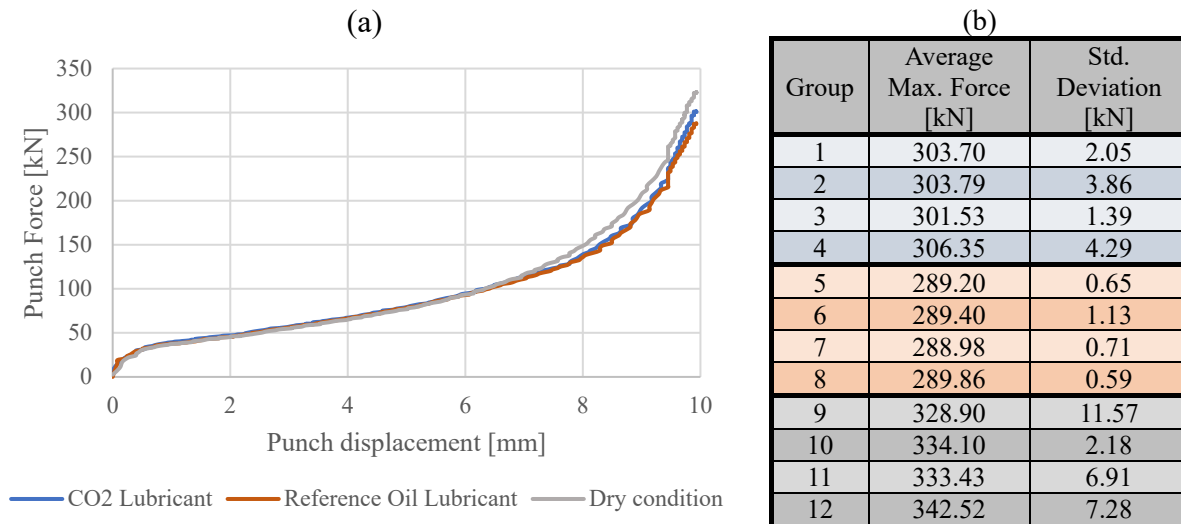


Fig. 6. (a) Force–displacement curves illustrating the three tested lubricants; (b) mean values and standard deviations of the maximum force measured during the miniature spike experiments (average results of three independent tests performed for each parameter group).

From the initial analysis, some conclusions can be drawn regarding the performance of CO₂ snow as a lubricant in cold forging—i.e. sample groups 1-4. Experiments conducted with CO₂ snow show, on average over all groups, 5% higher forming forces compared to tests using the reference oil lubricant.

In comparison, forming forces captured in the tests conducted without any lubricant were 10.2% higher than those observed with CO₂ and 15.7% higher than with the reference oil. These results clearly indicate that the use of CO₂ as a lubricant leads to a relevant reduction in forming forces compared to unlubricated conditions. These results demonstrate the effectiveness of CO₂ snow in reducing friction during cold forging.

Further, a representative miniature spike sample is shown in Fig. 7. Whereas Fig. 7a shows a sample from sample group 12 which represents high-friction conditions (dry lubrication) and Fig. 7b shows a sample from sample group 7 which represents low-friction conditions (mineral oil). The most notable geometric difference between both parts lies in the final height of the pin. The high-friction sample resulted in a smaller final height of the pin and a larger diameter of the flange, while the low-friction sample exhibited a greater height of the pin with reduced radial expansion of the flange. Lastly, Fig. 7c provides a summary of produced dimensions of the tested specimens.

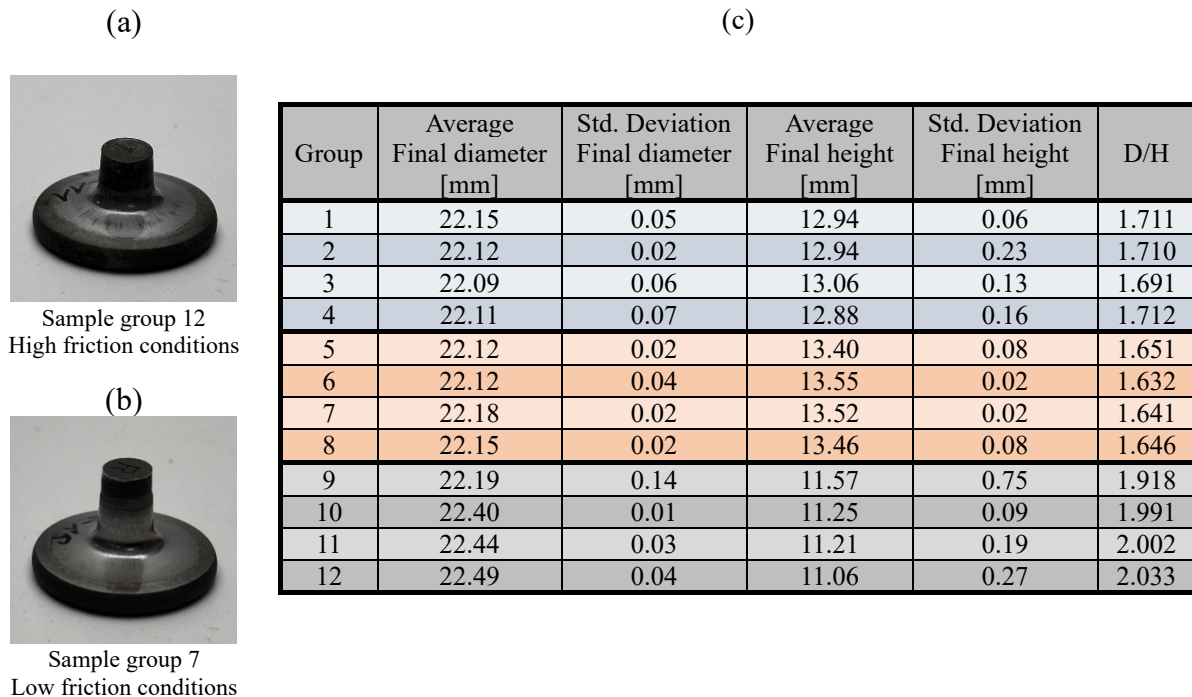


Fig. 7. Comparison of the specimen final geometry under (a) low- and (b) high-friction conditions; (c) final diameter and height measurements (average results of three independent tests performed for each parameter group).

The observed geometric differences can be attributed to the friction-dependant material flow during the spike test. When friction at the die–workpiece interface is low, the material experiences little resistance and is able to flow more easily along the die wall. This favours the material flow into the pin of the pressed spike part. In contrast, high friction conditions hinder sliding and restrain axial material flow. As a result, the material is forced more radially outwards, leading to a more pronounced flange and a lower spike height. The spike geometry therefore serves as a direct indicator of the interfacial friction conditions, enabling a clear distinction between efficient lubrication and high friction conditions.

The surface quality was assessed through roughness measurements. Fig. 8 presents a visual comparison of two representative samples, highlighting differences in the surface finish. Qualitative observation indicates that CO₂ snow lubrication results in a superior surface quality (Fig. 8a) compared to reference oil lubrication (Fig. 8b). In particular, an analysis of the flange region reveals that specimens processed with CO₂ snow lubrication exhibit a noticeably shinier appearance, whereas oil-lubricated specimens show a duller surface. This observation is further supported by quantitative roughness measurements which report the arithmetical mean height S_a values for each tested condition, presented as bar charts in Fig. 9a and in tabular form in Fig. 9b.

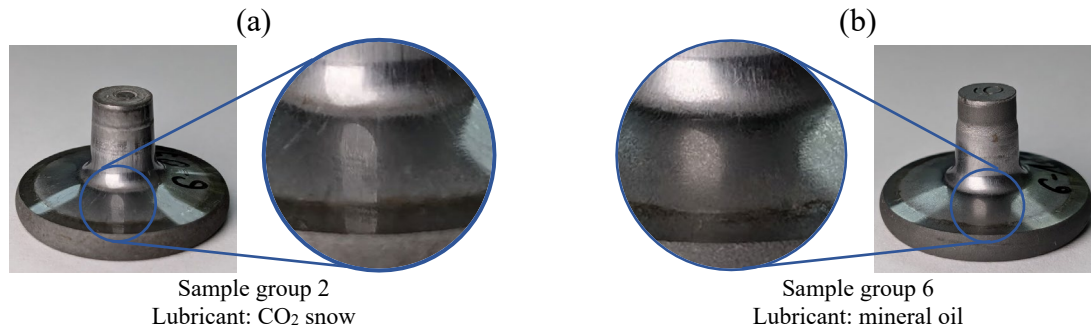


Fig. 8. Post-experiment visual comparison of the surface finish achieved with CO₂ snow lubrication versus mineral oil lubrication.

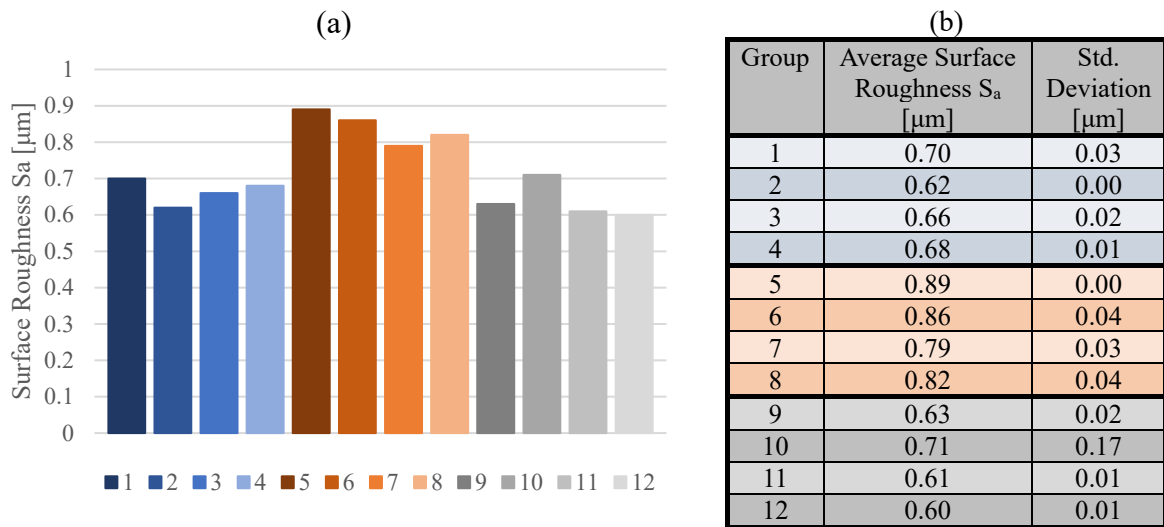


Fig. 9. (a) Surface roughness S_a measured for each tested parameter set after the experiment; (b) average values with standard deviations for each group.

Compared to the reference oil used in this study, CO₂ snow consistently produced smoother surface roughness in all tested cases. This supports the conclusion that CO₂ can be effectively used as a lubricant when improved surface quality is required. Relative to the initial state, all lubrication conditions demonstrated good performance, enhancing the surface by reducing roughness and producing a more uniform finish.

Conclusions

This study investigated the performance of CO₂ snow as a lubricant in the cold forging of mild steel (C15E) through an experimental approach. Miniature spike tests—widely used to evaluate friction characteristics—were conducted under various lubrication and surface conditions to assess frictional behaviour based on the forming forces required and the resulting dimensional changes of the specimens. The key findings of this work are summarized as follows:

- CO₂ snow significantly reduces forming forces compared to unlubricated, with average forces approximately 10% lower than unlubricated conditions.
- Reference mineral oil achieves slightly lower forming forces than CO₂ snow, though the difference is relatively small in the order of 5%.
- CO₂ snow consistently produces smoother surface finishes, indicating its suitability for applications requiring improved workpiece quality while avoiding residue and cleaning steps.
- For the range of roughness values tested within this study, no clear trend was observed between initial surface roughness and lubrication efficiency. Furthermore, no direct correlation between initial and final surface roughness could be derived.

- Both CO₂ snow and mineral oil improve surface uniformity relative to the initial state, demonstrating effective friction control.

In conclusion, CO₂ snow has been demonstrated as a viable alternative to conventional lubricants in cold forging of steel. It effectively reduces friction and enhances surface quality. Overall, CO₂ snow emerges as a promising residue-free lubricant, offering a practical pathway towards more sustainable and environmentally friendly cold forging processes.

Outlook

Following the results of this study, future work will potentially address the following aspects to further investigate the use of CO₂ snow in cold forging:

- Development of a FEM model to determine friction factors for the tested conditions, enabling the use of these values in future simulations for the design and optimisation of cold forged components.
- Design of an automated CO₂ snow application system to ensure uniform and controlled lubrication application across workpiece surfaces.
- Extended experimental campaigns to evaluate the effect of CO₂ snow on die surfaces over longer production runs, including surface degradation, with the aim of supporting high-volume or repeated part manufacturing.

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