The Quaker Houghton Multi-functional Reversing Mill: Research on and for rolling

This paper introduces the Quaker Houghton Pilot Mill and its capabilities. We demonstrate how a rolling mill can benefit research and development of product formulation, lubrication mechanism study and modeling through three case studies, covering: the correlation between coefficient of friction (CoF) and strip surface texture, validation of mathematical models with pilot mill data, and next-generation product development for steel cold rolling.

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Parameters	Typical value
Back-up roll diameter	400 mm
Max. roll force	1,200 kN
Main motor power	400 kW
Tension reel power	200 kW
Work roll diameter	165 mm
Work roll width	300 mm
Max. rolling speed	1,200 m/min
Max. tension	30 kN
Strip width	100-200 mm
Min. output strip thickness	0.1 mm

Table 1 **Technical parameters of the pilot mill**

INTRODUCTION

Cold rolling is widely used for steel sheet processing, where steel strip passes along sets of work rolls at temperatures below its recrystallization temperature. Lubricant composition and application play a key role in dealing with wear, friction, and lubrication in the roll bite as well as fulfilling other quality and environmental requests, including improving surface quality and reducing energy consumption. There is a lot of different laboratory equipment required to evaluate a lubricant's lubricity, washing-off and corrosion protection, among other properties. However, in most cases, these devices only partially reflect the performance of a lubricant. To evaluate a rolling lubricant comprehensively, a pilot rolling

Fig 1 **The Quaker Houghton Multi-functional Reversing Mill**

Parameters	Emulsion system	Cleaning system	DA system
Max. volume	3,150 L (3.1 m^3)	1,500 L	70 L
Flow rate	100-600 L/min	300 L/min	1.5 L/min
Max. pressure	5 bar	5 bar	1.5-2.0 bar
Max. heating	90˚C (194˚F)	90˚C (194˚F)	70˚C (158˚F)

Table 2 **Fluid system parameters of the pilot mill**

mill is the most realistic application scenario. Located in Qingpu District, Shanghai, China, the Quaker Houghton Multi-Functional Reversing Mill (hereinafter the Pilot Mill) was constructed between 2013 and 2014, and successfully commissioned and put into operation in 2016. It is able to evaluate lubricants thoroughly through various rolling schedules, rolling speeds and steel types (*Figure 1*).

PILOT MILL PARAMETERS AND CAPABILITIES

The Pilot Mill, a 4-high, backup roll-driven, multi-functional high-speed reversing mill with the technical parameters as in *Table 1*, contains nine main mechanical components and fluid systems (*Figure 2 & Table 2*). It is equipped with three fluid systems: emulsion, cleaning, and direct application (DA) systems, so the lubricant can not only be supplied by the emulsion system, but also in DA mode, independently or in combination with emulsion circulation. Moreover, unique to the mill is a cleaning line, which ensures that any contaminants on the incoming materials are removed and do not impact test results.

Both soft and hard steels can be processed on the Pilot Mill with multiple process settings. This not only fulfills our scope for a basic chemistry and mechanism study, but also supports product technology optimization and next-generation product development, helping to de-risk fluid upgrades for our customers. More specifically, in combination with our extensive lab equipment and test capabilities, the Pilot Mill can conduct:

1. Basic chemistry and mechanism studies

Different chemistries and mechanisms behind lubricant performance for either soft or hard steel rolling have been explored extensively with the Pilot Mill, based on theories of cold rolling and tribology. Among all the crucial lubricant performance criteria, including lubrication, cleanliness, anti-corrosion and cooling, lubrication has been studied most extensively. We've investigated the effect of lubricant composition including extreme

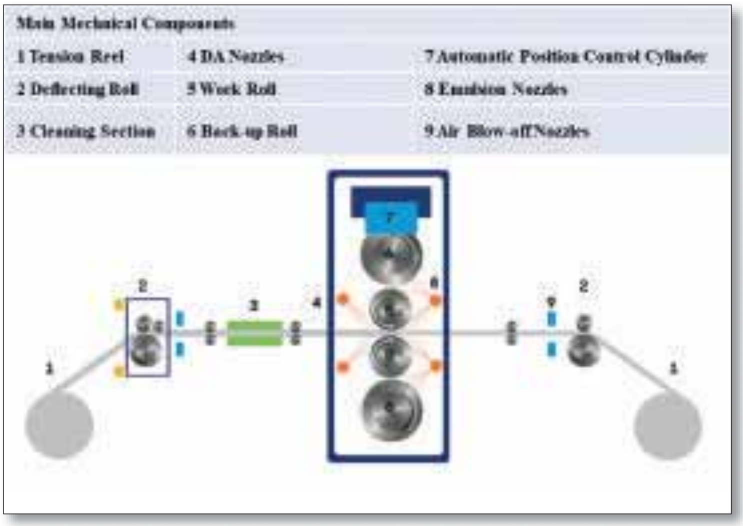

Fig 2 **Pilot mill stand schematic**

pressure and anti-wear additives on roll force, current, and forward slip; tested influences of contaminants and pH variations; and validated and calibrated test methods and mathematical models for lubrication and other properties.

2. Product technology optimization

Different product technologies, either cationic- or nonionic-based lubricants, and performance-optimizing solutions, can be rigorously evaluated and compared under real rolling conditions, which guarantees robust field performance and offers insights for onsite troubleshooting. The Pilot Mill facilitates optimizing products for cost-efficiency, rolling performance, and waste treatment; investigating lubricity performance in relation to mill conditions by generating "Stribeck curves", and evaluating product applications such as influences of emulsion conditions and neat oil properties on aspects such as lubrication and cleanliness.

3. Next generation rolling fluid development

With a growing industry focus on both sustainability and productivity, there are increasing requests for lubricants in terms of high-speed rolling, energy saving and reduced

Pass no.	Incoming gauge (mm)	Target reduction (%)	Back tension (MPa)	Front tension (MPa)	Exit speed (m/min)
Pass 8a	0.24	29.2	80	140	100
Pass 8b	0.24	29.2	80	140	400
Pass 8c	0.24	29.2	80	140	800
Pass 8d	0.24	29.2	80	140	1000

Table 3 **Rolling details in pass eight**

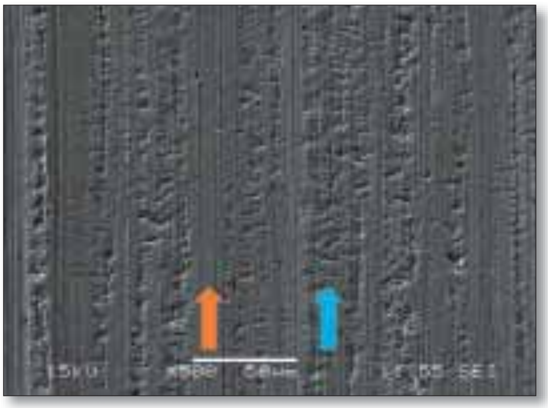

Fig 3 **SEM image of a typical cold rolled strip surface**

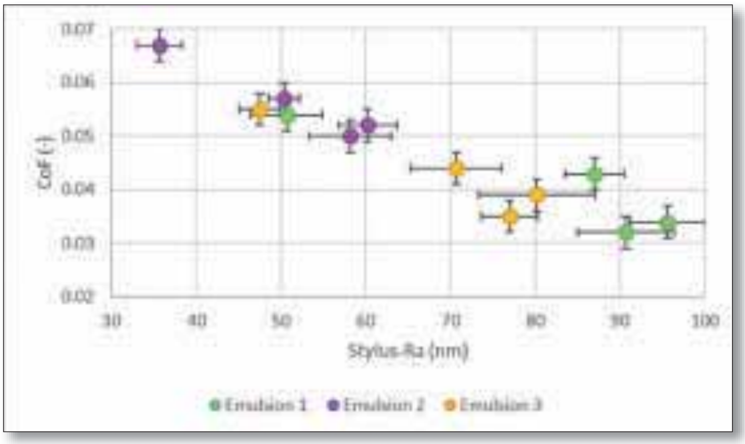

Fig 4 **Plot of coefficient of friction in the trials versus the Stylus-Ra roughness in the rolling direction**

environmental impact. Besides conventional product evaluation and optimization, we are also exploring ground-breaking technologies to further fulfill ever-evolving customer needs. The Pilot Mill allows us to validate novel lubricant concepts and product performance, accelerating progress in new product development and de-risking the adoption of innovative technologies.

The three case studies below demonstrate typical research work with the Pilot Mill.

CASE STUDY 1 – THE CORRELATION BETWEEN COEFFICIENT OF FRICTION (COF) AND STRIP SURFACE TEXTURE

With a research facility such as the Pilot Mill, trials can be designed to explore and validate lubrication mechanisms. In a series of trials it was investigated how speed and lubricant composition influence friction. This was done in an 8-pass trial with a speed variation in pass eight using a soft steel type. The trial was conducted for three lubricant emulsions, which were all carried out in duplicate. Details of the last pass schedule can be seen in *Table 3*. An in-house rolling model was used to calculate the CoF during the trials. The strip surface was also analysed after the trials using a scanning electron microscope (SEM) and an optical surface profiler.

Cold rolling occurs in the mixed lubrication regime: local areas of close contact between work roll and strip coexist next to local areas of higher separation. The areas of close contact are the areas where boundary lubrication conditions exist locally, characterized by relatively high friction and, due to the close contact between the work roll sliding over the strip, the presence of mild grooving on the strip. The areas of higher separation are the areas where elasto-hydrodynamic lubrication (EHL) conditions exist locally, characterized by relatively low friction and, due to the relatively unrestrained reorientation of stressed crystal grains, the presence of transverse fissures, mainly in the roughness valleys. These surface features are

	Viscosity base oil (mPas)	Emulsion concentration (%)	Oil particle size (mm)
Emulsion A	59.3	2.56	10.1
Emulsion B	58.4	2.55	2.1
Emulsion C	116.2	2.50	12.5

Table 4 **Lubricant and emulsion properties**

clearly visible in *Figure 3*, where mild grooving is shown by the orange arrow and transverse fissures by the blue arrow. The stylus roughness in the rolling direction is higher for the latter.

The ratio between mild grooving and transverse fissures is thus a measure of the lubrication regime and can be quantified by the 'stylus' Ra roughness in the rolling direction **[1]**. During rolling, the lubrication regime is influenced by rolling speed (higher speeds lead to a higher contribution of EHL) and lubricant performance (better lubricants give higher film formation and a higher contribution of EHL). Thus, the lubrication regime influences both friction and the surface texture, i.e. the ratio between mild grooving and transverse fissures quantified by the stylus Ra value in the rolling direction.

In Figure 4 it can be seen that this is indeed the case. The graph comprises data for three emulsions at four speeds, so the correlation between friction and surface texture is universal, whether it is caused by speed or lubricant.

CASE STUDY 2 – VALIDATION OF MATHEMATICAL MODELS WITH PILOT MILL DATA

The Pilot Mill is also ideally suited to validate mathematical rolling models. Quaker Houghton has contributed to the development of a tribological roll bite model featuring lubricant and emulsion parameters **[2]**. Using this model, the influence of properties such as viscosity, viscosity-pressure index, boundary friction, plate out, emulsion concentration, and oil particle size, can be explored theoretically, and then validated in well-defined trials.

Three lubricant emulsions were tested on the Pilot Mill, varying in base lubricant viscosity and oil particle size in the emulsion (*Table 4*). Generally, and all other aspects being equal, a higher viscosity and higher oil particle size would lead to lower friction and roll forces. The trials comprised of eight passes, which were also modelled using the rolling model and the full range of required lubricant and emulsion properties. The CoF values calculated from the roll forces in the pilot mill were then compared with the calculated CoF values.

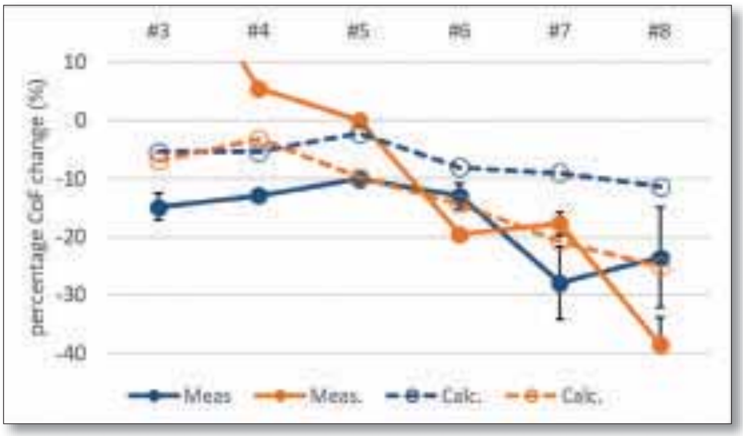

Fig 5 **Percentage change in CoF for the best and worst lubricants, comparing viscosity (orange), and oil particle size (blue), measured on the mill (solid lines) and calculated (dashed lines)**

Figure 5 shows the reduction of the CoF with the better lubricant emulsion (having a higher viscosity and higher particle size) compared with the worse one, i.e. emulsion C is compared with A (having a higher viscosity and similar particle size), while emulsion A is compared with B (having a higher particle size, but similar viscosity). The figure shows that increasing the viscosity results in a 10-40% roll force reduction, which is well predicted by the calculations, except for pass three. An increase in particle size results in a 10-30% decrease in friction, which is slightly underestimated by the calculations.

CASE STUDY 3 – NEXT GENERATION PRODUCT DEVELOPMENT FOR STEEL COLD ROLLING

To meet customer needs, we are dedicated to providing fluid solutions to advance lubricant technologies safely and sustainably. Led by our green chemistry guidelines to reduce harmful and fossil-based raw materials, and with the goal of developing a sustainable and easy to handle steel rolling fluid, different chemical concepts have been screened on the Pilot Mill and compared with traditional oil-based

Pass No.	Incoming gauge (mm)	Target reduction (%)	Back tension (MPa)	Front tension (MPa)	Exit speed (m/min)
Pass 1	2.00	16.00	38	58	80
Pass 2	1.68	25.00	42	100	100
Pass 3	1.26	30.16	48	140	200
Pass 4	0.88	34.09	50	145	300
Pass 5	0.58	39.66	55	140	400
Pass 6a	0.35	34.29	60	140	100
Pass 6b	0.35	34.29	60	140	600

Table 5 Pass schedule for the Pilot Mill trial for the Aqueous Fluid Product

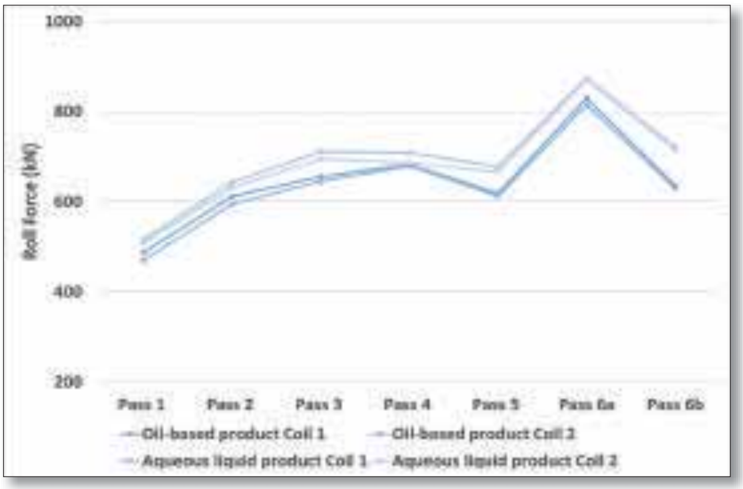

Fig 6 Roll force comparison, oil-based product vs. aqueous fluid product

products. *Table 5* shows the pass schedule for a trial involving an aqueous fluid product. The roll force results in Figure 6 show that the aqueous liquid product, with a concentration of 8%, performs similarly to the oil-based product, with a concentration 2.5%, and with good repeatability. This is a promising step toward delivering an innovative, sustainable aqueous fluid technology with excellent performance.

CONCLUSION

By combining Pilot Mill trials with SEM and optical surface profiling, aspects of lubrication mechanisms were validated. The ratio between mild grooving and transverse fissures indicated different lubrication regimes resulting from either rolling speed or lubricant properties. Mathematical models were also validated and improved with Pilot Mill data. Such modeling allows us to investigate the effects of lubricant parameters to better predict field performance and offer robust solutions to customers. By exploring and advancing new chemical concepts with the Pilot Mill, we can accelerate new product development and de-risk adoption of innovative technologies today and in the future. MS

REFERENCES

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