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Lubricant for clean rolling

Escapee oil particles keep cold rolling steel mills lubricated



Astrid van de Graaf

One of the unique selling points of the Corus steel mills at IJmuiden is the quality of the steel they produce. The lubrication used during the last production stage is one of the factors that determine how clean and smooth the steel will emerge from the mill. The usual lubricant consists of an emulsion of oil in water. Until recently, little was known about the physical principles underlying the action of lubricant emulsions in steel mills. The only way to test new lubricants was by applying them during the actual production process. Physicist Marjolijn Trijssenaar of the subfaculty of The quality of steel depends not only on its composition, but also on the ways in which it is rolled. In the traditional production process, the first stages of the rolling process (from a thickness of approximately 22 cm to a few millimetres) take place at temperatures in excess of 800°C. The last stages – if required – are done using the cold rolling process. Applied Physics Delft University of Technology has changed all this. She managed to unravel the complex chemical and physical processes that take place in the roll gap during cold rolling, and to translate this knowledge into a model that can be used to describe and optimise the lubrication process.

The old adage, «strike while the iron's hot», does not apply in every case. There is also the cold method, at least for rolling in the steel production industry. Cold rolling is one of the last stages in the production process of strip steel. Slabs of steel are rolled, first hot, and then cold if necessary, into strips several kilometres long and a few tenths of a millimetre thick. At the end of the process the speed at which the material travels through the mill is over 70 km per hour. Yet cold rolling is a relative term, for the rolling process causes the temperature of the steel to increase so much that cooling water has to be continuously sprayed onto the steel strip and the rolls. Instead of ordinary tap water, the coolant is an emulsion of water, rolling oil, and an emulsifier. The emulsifier molecules, which consists of hydrophobic and hydrophilic parts, ensures that the oil can «float» in the water as finely distributed particles. The very fine oil droplets, just about 3.5 micrometres in diameter, are enveloped in a single layer of emulsifier molecules, which prevents them from sticking together, and thus helps to keep them suspended in the water. Using an emulsion as coolant ensures that both the rolls and the steel strip are lubricated at the same time. The lubricating oil reduces the friction between the roll and the steel strip, which are pressed together at high pressure. The result is that wear and tear on the rolls is reduced, and the rolled steel strip comes out nice and smooth.

Health reasons

The composition and the action of the rolling emulsion are essential to the production process and for the quality of the steel. Too much lubrication, and the steel cannot be pulled through the mill, because the rolls will slip on its surface. Too little lubrication, and the resulting friction may cause the steel surface to become severely polluted and damaged. On top of that, the roll power may be insufficient to achieve the desired reduction rate.As a result of these quality requirements, and more recently, environmental and health requirements, manufacturers of rolling oil are continuously introducing new, sometimes better, products. Although the lubricant manufacturers can provide standard specifications such as viscosity, density, and toxicity, their insight into the rolling process itself tends to be limited, since they are unable to conduct field tests. It isn't until production has actually started that the steel manufacturer finds out whether a new type of oil really is an improvement over the old one. If the test fails, the production run becomes a very expensive experiment. Extensive research has provided the theoretical basis for the action of pure rolling oil but the lubricating action of emulsions during cold rolling remained somewhat of a mystery.



Steel production process



View of the hot rolling train at the Corus steel mills IJmuiden in the vicinity of Amsterdam. The annual production is approximately 4.8 Mt.

Colloidal chemistry

To find out more about the physical principles underlying the lubrication during cold rolling, researchers of Corus, what was then still called Hoogovens, knocked on the door of Professor Dr. Gert Frens of the Physical Chemistry section at the department of Chemical Engineering, with whom they already had a working relationship. Frens, who is an expert in the field of colloidal chemistry, and physicist Ir. Marjolijn Trijssenaar took up the challenge. Trijssenaar: 'We thought it was an ambitious project, in particular because very little on the subject can be found in existing literature. Even if other steel manufacturers had collected data, competition meant that these had never been published. So, we started with a practically clean slate.'

To Trijssenaar herself, it was all new anyway. During her graduate research at the Applied Physics faculty she had worked on process control systems for waste water processing plants and for robots, such as paint robots for the car industry, and now she was about to take on board colloidal chemistry and mechanical engineering, or more precisely, the behaviour of oil particles in emulsions and rolling technology. Pure oil cannot be used in the cold rolling process, for this would soon render the steel strip too greasy. Oil in a highly diluted form is thus applied as an emulsion. The interesting question facing an engineer of colloidal chemistry is how the oil particles, suspended as they are in an excess of water, can still perform their lubricating function. 'That's exactly what attracted me about this research: the complexity and variety. The combination of the theoretical scope and the actual mill tests made me choose this as a research subject. What's more field data and theoretical insights had to be translated into a model that can be used to describe and optimise the physical and chemical properties of roll emulsions,' Trijssenaar explains.

Crumpled

By that time, Hoogovens Research & Development has just completed the installation of a set of laboratory rolls of German manufacture. For production runs, the cold rolling mill uses a series of five pairs of rolls. Since the testbed only has one pair of rolls, the steel test strip has passed to and fro five times. The testbed features coilers at each end to reel the steel strip in and out. 'On a laboratory scale, the behaviour of emulsions is sometimes tested in a setup consisting of a steel ball pressing against a revolving steel disc, but this is not a good enough simulation of the lubricating processes that occur during the cold rolling process', Trijssenaar says. The availability of the testbed did not mean that Trijssenaar herself could go to work on it. Running the test rig, which is about seven metres long and three metres high, takes two or three operators. Trijssenaar provided the instructions for programming the computers that control the set. The operators also handled the fitting and removal of the coils of steel. Trijssenaar was allowed to cut the occasional sample from the rolled steel, though.

'When we started, nobody knew what the installation



Side view of a set of work rolls during the reduction of a steel strip.



Cold mill 21 is a production mill. Customers of its products include the car and household appliance industries, but not the packaging industry (tins). The work rolls on the right are spares.



Schematic diagram of a cold rolling set containing two work rolls and two, larger, backup rolls. The parameters used by Marjolijn Trijssenaar for her research are the speed of both the steel strip and the roll, the roll pressure, and the entry and exit tensions. could do, so the first tests were used to explore the capabilities of the test rig. Of course, things went wrong a few times, but once you've had to extract some lengths of crumpled steel from a rolling plant a few times, you tend to become more cautious', Trijssenaar recalls.

Shopping list

The steel passed through the rolls at a speed of about one metre per second (which is slow, compared with a production mill), so an experiment involving a few hundred metres of steel strip does not take very long. Most of the time went into planning the experiments, preparing the equipment settings, taking the samples after each pass, and the analysis afterwards. Well in advance of each test run, Trijssenaar had to hand in a shopping list specifying the required length of steel strip, the quantities and types of emulsions, and the data for the test conditions. During her preparations she was assisted by her supervisor, Frans Suilen of Hoogovens R&D (now Corus Research, Development & Technology), who also took care of booking the necessary operators.

'Compared with field tests during the actual production process, these experiments are relatively cheap,' Trijssenaar says. After a week of experimenting, she had collected enough data to keep her occupied for months processing and interpreting the results, and in particular extracting every last ounce of information. The laboratory testbed was used to run a total of four extensive, well-prepared test sequences, excluding the initial, exploratory tests.

Infrared spectrometry

The oil film thickness on the rolled strip is a measure of the performance of the lubricant. The oil film is invisible to the naked eye. The thickness of the film is of the order of magnitude of 0.1 micrometre, which is nothing compared with the irregularities of the material surface, which measure between 0.5 and 0.3 micrometre. The mill roll itself has a certain roughness, which it needs to get a proper grip on the steel strip. At the same time, the roll surface acts as a stamp, so the roughness of the rolled strip does not decrease as the strip becomes thinner and longer.

As a result of the rolling process, the strip is stretched. Unless the quantity of oil is replenished, the stretching process would cause the oil film to become much thinner as it has to cover a much larger surface. To keep the oil film on the steel strip at the required level, it has to be replenished with oil from the emulsion that is sprayed onto the material. In principle there is no shortage of oil. During the rolling process, an excess of emulsion, which contains about 2.5 percent lubricating oil, is sprayed onto the steel strip and the rolls from a series of nozzles. Where and how the oil particles moved during the rolling process from the emulsion into the thin oil film on the strip was one of the questions Trijssenaar was brought in to answer.

To determine the thickness of the film of oil after rolling, sections of steel were cut from the rolled strip, and rinsed in Freon, which dissolves the oil (due to



In spite of what the name suggests, cold rolling does involve high temperatures, up to about 400 °C. Since the process involves high pressures with steel facing steel, proper lubrication is essential, as is cooling to cope with the high temperatures. If the oil/water mixture can no longer cope, the rolling process is affected, and the results can be bizarre.



Cold-rolled steel ready for industrial use.



The testbed used by Trijssenaar for her research on optimal lubrication during cold rolling.

environmental considerations, alternative methods are now being used). The oil concentration in the wash was determined using infrared spectrometry. The quantity of oil particles that actually ended up from the emulsion spray in the oil film was calculated by taking differential measurements between consecutive roll passes. The results indicated that the preset reduction rate (thickness per pass) was the determining factor. As the reduction rate increased, more oil particles passed from the emulsion to end up in the oil film during rolling, which is exactly what makes a good cold rolling process.

Trijssenaar: 'This does not mean that we can recommend simply increasing the reduction rate in the production plant, for the capabilities of the system are limited by the pressure of the roll and the resulting heat development.'

During the rolling process, wear and tear of the roll, or damage to the strip can cause steel debris to land on the surface. After all, the two metal surfaces meet with a pressure in the order of magnitude of one GPa. Good lubrication can prevent wear. In addition, cold rolling will always remain a kind of balancing act between strip tension, equipment power, and slip.'

Contact zone

Reproducibly measuring the thickness of the oil film was one thing, but providing a scientific explanation for the action of the lubricant was a different story. To begin with, Trijssenaar tried to determine at what point the lubricant particles precipitated from the emulsion. Was it the contact zone, i.e. the bit where the steel strip and the roll touch, or the entry zone, the area just before the steel strip and the roll meet. The latter place is where most of the emulsion gathers due to the excess of lubricant fed onto the material. There was a notion that the precipitation of the oil particles from the emulsion took place in the contact zone. A series of rolling tests on a smaller, hand-operated roll, during which the thickness of the emulsion layer under the roll was measured, soon changed all that. Surprisingly, the thickness of the emulsion layer in the contact zone was much too small to explain the thickness of the oil film measured on the material. So, the oil particles had to be escaping from the emulsion at an earlier point, i.e. in the entry zone.

'On the other hand, the film thickness of the emulsion in the contact zone proved to be much greater than we initially thought it would be, so the results were rather unexpected. Looking back, this can be explained by the fact that model calculations are always based on the ideal case with a smooth surface. A rough surface can pick up quite a lot of emulsion. These are very complicated calculations that take a lot of time', as Trijssenaar now knows.

Laminar flow

So the oil film had to be formed in the entry zone. It was difficult to find a theoretical explanation for the escape of the oil particles, all the more so because the area is subject to the rules of laminar flow in liquids, and all the



The test roll carries sensors to provide on-line readings of the roll pressure, the turning speed of the work roll, and the reduction rate, so the rolling process can be monitored and changed on the fly.



To get an impression of the action of the emulsion as it was used during production, Marjolijn Trijssenaar started by measuring the thickness of the oil film on the rolled steel. The films varied in thickness between 50 and 190 nanometres for varying reduction rates. The reduction rate is expressed as:(thickness in – thickness out) : (thickness in) x 100%



Trijssenaar concluded from her research that the reduction rate was the determining factor for the precipitation of oil on the rolled steel. Remarkably, this proved to be independent of the type of oil and the type of emulsifier.

particles move with the flow. The emulsion on the steel strip moves with the strip at a constant speed in the direction of the roll contact point. The emulsion on the roll also moves in that direction. There is an accumulation of excess emulsion in the contact angle between the roll and the strip. Just before the roll and the strip meet, the two liquid flows collide, and the excess emulsion is pushed back through the middle of the contact angle. A very small quantity of the emulsion ends up between the roll and the strip. Model-based calculations of these flows showed that the shape of the flow profiles, like the oil film thickness readings, depended on the reduction rate. The speed at which the rolled strip leaves the machine is slightly higher than the turning speed of the roll. Since the strip becomes thinner and stretched by the rolling process, the speed of the steel strip is much lower before it passes through the rolls. As the reduction rate increases, the difference in speed between the roll and the strip as it enters the rolls increases, which results in a highly asymmetrical distribution in the flow profile of the emulsion in the entry zone.Old scientific literature provided the solution for the theoretical basis of the processes that occur in these emulsion flows. Trijssenaar: 'As early as 1962, Mr. Segré, of the Weizmann Institute of Science in Israel, wrote that particles in a flow can migrate transversely to the flow lines as a result of the so-called inertia effect. The particles moved towards a position of equilibrium, which in this case is either towards the strip or the roll. The segregation of the oil particles from the emulsion reaches its maximum in the angle where the strip and the roll almost come into contact with each other. The oil concentration increases at that point of the entry zone. In the contact zone I have measured increases to as much as 30% oil. So, the entry zone contains a highly enriched emulsion.'

Using this information, Trijssenaar was able to provide a theoretical explanation for what she had already measured in tests, and so she was able to define a model for the process.

Statistics

The complexity of the subject matter and the tests took a few extra years of research. After six years of playing around with rolls and model parameters, not only do Trijssenaar and Corus have a working model of the lubrication process, but Corus has also become an equal partner in discussions with rolling lubricant manufacturers. Trijssenaar had to take another three months unpaid leave to perfect the model and complete her thesis.

Overlooking The Hague and the dunes along the North Sea from her office on the eleventh floor of the building of the government agency Statistics Netherlands, she looks back on these last efforts with satisfaction. The next equally ambitious project is in the offing: developing the quarterly financial accounts for the various different sectors of the Dutch economy. These accounts will soon be used by the European Union to monitor the economic developments in every member state.



A simple test was used to determine the thickness of the emulsion film between the roll and the steel strip at various reduction rates. An aluminium strip onto which a drop of emulsion had been placed was fed through a manually operated set of rolls. The surface area of the resulting patch and the volume of the drop before rolling provided the film thickness.



Schematic representation of the contact between the work roll and the steel strip. Important parameters include the radius of the work roll, the turning speed of the roll, the speed of the steel strip, the thickness of steel strip as it enters and leaves the rolls, the angle between the incoming strip and the roll, and finally, the height and length of the entry zone (i.e. the area between the roll and the strip just before they make contact).



Schematic representation of the flow in the entry zone. Lubricant is carried along by the surfaces of the roll and the steel strip, and is pushed back through the centre of the entry zone. Only a small fraction of the lubricant ends up in the contact zone between the roll and the strip. How's that for something completely different? n

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The figures above show the direction and the speed of the lubricant in the entry zone. The entry zone is limited by the surface of the steel strip (the horizontal line at the bottom) and the surface of the roll (the curved line at the top). The three figures show the effect of the reduction rate on the speed profiles. In figure A, the reduction rate is nil, and the speed profile is fairly symmetrical. Increasing the reduction rate changes the shape of the speed profile. In figure B, the reduction rate is 0.166, and the speed profile has become more asymmetrical. As the reduction increases, the backflow moves closer to the steel strip. In figure C, with a reduction rate of 0.457, the speed profile is even more asymmetrical.

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Segregation occurs in the entry zone, i.e. the oil phase and the water phase separate more or less. This is caused by the migration of the oil droplets in the emulsion to specific locations in the entry zone. As a result of this, certain locations in the entry zone become enriched with oil. The figure shows the segregation number. A segregation number of zero indicates a homogeneous distribution of particles, higher numbers indicate increasing separation in the entry zone. At a point about three quarters into the entry zone, segregation clearly occurs. Increasing the speed during rolling results in the segregation shifting to a point earlier on in the entry zone.

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