Journal of Materials Processing Technology 223 (2015) 164–170

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Wear debris generation during cold rolling of stainless steels

Wilian da S. Labiapari[a,b], Cláudio M. de Alcântara[b], Henara Lillian Costa[a], José Daniel B. De Mello[a,*]

[a] Universidade Federal de Uberlândia, Laboratório de Tribologia e Materiais, Campus Sta. Monica, Bloco 1M, Uberlândia, MG 38400 901, Brazil
[b] R&D Department, Aperam South America, Praça 1 de Maio, 09, Centro, Timóteo, MG 35180-314, Brazil

ARTICLE INFO

Article history:
Received 5 December 2014
Received in revised form 23 March 2015
Accepted 28 March 2015
Available online 8 April 2015

Keywords:
Cold rolling mills
Stainless steel
Pollution
Wear debris

ABSTRACT

The production of pollution can be a significant industrial problem during cold rolling. Pollution is often attributed to the formation of wear debris during rolling, which mixes with the lubricant oil used to cover the rolled sheet. The cleanliness of the rolled sheet, its consequent aesthetics, and the downstream performance of the process are affected by the production of pollution. In the first stage of this study, the pollution formed during industrial cold rolling was collected and found to be composed of a mixture of small stainless steel debris and lubricant. Second, the study investigated the effect of rolling conditions on the generation of wear debris. Tests were carried out using laboratory cold rolling mills. The effects of the type of stainless steel (ferritic or austenitic), of the surface finish of the sheets before rolling, of the thickness reduction ratio, of previous annealing of the sheet, and of lubricant temperature on the wear of sheets due to rolling were investigated. Cold rolling resulted in weight reduction of the sheets due to the formation of wear debris. Weight loss for sheets finished by conventional acid pickling was greater than for sheets finished using shot blasting. A further reduction in the wear of the sheets due to rolling was observed when their surface roughness was decreased by polishing. An increase in the thickness reduction ratio lowered the elongation to fracture of the rolled sheets and increased their wear. Previous annealing of the sheets was then used to successfully reduce wear of the rolled sheets. An increase in the temperature of the oil used during rolling increased wear of the sheets due to rolling. Finally, industrial trials were carried out applying the rolling conditions that had resulted in lower weight loss for the sheets during the laboratory-scale tests. This significantly reduced the amount of pollution produced during industrial cold rolling of stainless steel, improving the final quality of the product.

1. Introduction

To improve productivity and product quality during cold rolling, the variables that affect the process need to be understood and controlled (Huart et al., 2004). Friction during rolling has a significant influence on the dimensional accuracy and surface quality of the rolled strip. Jiang et al. (2008) modelled friction during cold rolling, showing that variation in friction along the roll bite and along the strip width significantly affects rolling performance.

The use of lubricants during rolling contribute to limiting torque and rolling forces by maintaining sufficient friction for the sheet to be driven forward without slipping (Deltombe et al., 2003). A combination of low forward slip and small friction coefficients is expected to result in adequate rolling conditions. However, if the forward slip is too small, the rolling system can become unstable. The use of lubricants affects the surface finish of the rolled sheet and the precision and stability of the rolling process (Lin et al., 1991). The number of real metallic contacts between tool and workpiece decreases when lubricants are used, reducing friction and wear (Louaisil et al., 2009). However, tool and workpiece should not be completely separated by an oil film, because the workpiece would deform without any local constriction (Schey, 1983). This could lead to roughening of the sheet (Kawal et al., 1986) and increased wear (Januszkiewicz et al., 1994). Finally, lubricants help to cool the roll bite, where a large amount of energy is dissipated by friction and plastic strain of the sheet (Lin et al., 1991).

The high pressures involved in a rolling contact can induce wear of the contacting surfaces by various mechanisms: (i) concentration of shearing strain below the surface; (ii) ploughing by asperities; (iii) microcutting by hard, acute asperities, (iv) ploughing or cutting by hard detached wear particles; (v) repeated contact leading to fatigue or delamination wear; and (vi) detachment of oxides

---

[*] Corresponding author. Tel.: +55 34 32394036; fax: +55 34 3239 4273.
E-mail addresses: wilian.labiapari@aperam.com (W.d.S. Labiapari), claudio.alcantara@aperam.com (C.M. de Alcântara), ltm-henara@ufu.br (H.L. Costa), ltm-demello@ufu.br (J.D.B. De Mello).

http://dx.doi.org/10.1016/j.jmatprotec.2015.03.050
0924-0136/

or partly oxidized particles (Montmitonnet et al., 2000). All these mechanisms lead to the formation of wear debris, which may be either removed or remain within the contact (Xuan and Cheng, 1992). In the case of lubricated rolling, the debris remaining within the contact can promote the formation of a slurry, a mixture of lubricant and solid particles, called dirt or pollution (Huart et al., 2004; Krauth, 2002).

The cleanliness of sheets after rolling is important for aesthetic reasons. In addition, it affects its downstream performance in forming operations. In fact, a large amount of the pollution formed during rolling is removed by the lubricant used during rolling, but some residual dirt remains on the rolled sheet surface. The next step downstream in the cold rolling process is annealing, which restores the metallurgical structure of the sheet. Due to the high temperatures involved in the annealing process, organic elements such as oil lubricant and impurities reduce into carbon. Nevertheless, carbon and ferrous compounds remain on the surface of the sheet after annealing (Deltombe et al., 2003). In the case of carbon steels, which undergo subsequent galvanization, the contact of the metallic debris with the galvanizing bath creates a reaction called dross, in which the debris are dragged by the sheet. These residues slow down the coating mechanism during zinc plating, so that the zinc coat is locally weakened, decreasing the sheet corrosion resistance. In addition, the formation of pollution poses a considerable operational problem, because large amounts of debris may interrupt the filtration process, which is vital to maintain the cleanliness of the lubricant/refrigerating oil.

Rolling parameters can have a strong effect on the generation of wear debris, which will influence the formation of pollution and, therefore, the final surface quality of rolled products. It has been suggested that sliding length has major effect on detachment and/or adhesion of wear particles during forming (Montmitonnet et al., 2000).

Conventionally, sheets are pickled using acids before cold rolling, which results in a fairly large surface roughness. The use of rough sheets before rolling, in particular when associated with inadequate adjustment of the rolling parameters, can favour the formation of metallic debris during rolling (Huart et al., 2004). Cold rolling of sheets with initially rough surfaces can also lead to the formation of transfer layers that modify the local contact conditions, increasing rolling torques, rolling forces, temperature, and friction coefficient (Louaisil et al., 2009).

Another important rolling parameter is the lubricant temperature. First, higher temperatures reduce lubricant viscosity, resulting in thinner lubricant films. For example, in the case of cold rolling of aluminium can alloys, the increase of the sheet entry temperature reduced the amount of pollution, which was associated with the reduction in oil film thickness in the roll bite (Januszkiewicz et al., 1994). Second, the lubrication regime in cold rolling is mainly quasi-boundary (Huart et al., 2004). Since temperature has a great influence on the behaviour of the additives that are decisive for boundary lubrication, lubricant temperature cannot be neglected (Louaisil et al., 2009).

The use of large thickness reduction ratios during rolling and the rolling of harder sheets are expected to cause more wrenching of the asperities in the rolling contact and to affect the transfer layers formed during cold rolling. Therefore, thickness reduction and previous annealing of the sheets should have a strong influence on the generation of debris during rolling.

Various tribological tests have been used to study the generation of wear debris, from simple tests such as four-ball tests (Laugier and Ficara, 1999) to much more complex tests, such as upsetting rolling tests (URT) (Deltombe et al., 2003). Four-ball tests can compare oil performance using specific criteria (pressure, materials in contact, etc.) but real lubrication conditions between tool and workpiece during cold rolling are different from those simulated in four-ball tests. URT tests represent roll strip contact conditions much better and their use has helped to identify the effect of important rolling parameters such as reduction ratio (Deltombe et al., 2003; Huart et al., 2004), relative speed (Deltombe et al., 2003; Huart et al., 2004; Louaisil et al., 2009), pass number (Huart et al., 2004), rolling direction (Deltombe et al., 2003), interface temperature (Louaisil et al., 2009) and lubrication (Huart et al., 2004; Louaisil et al., 2009) on the amount of debris formed during rolling.

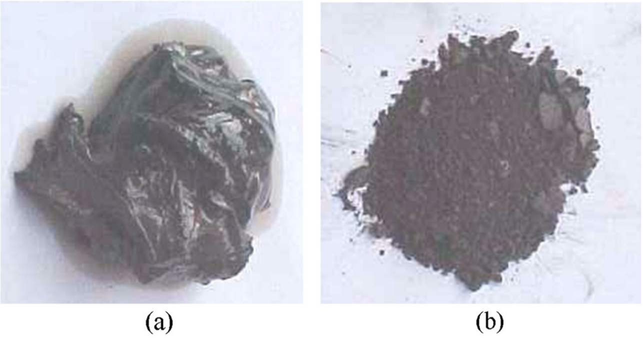

Fig. 1. Analysis of the pollution collected from industrial cold rolling of stainless steel: (a) pollution collected; (b) solid particles after oil separation.

Despite being more expensive, laboratory-scale cold rolling mills permit to take into account real industrial conditions (Laugier and Ficara, 1999). Jacobs et al. (2011) used cold rolling pilot mills to analyze the influence of rolling parameters on the cleanliness of carbon steel strips. In the present paper, a laboratory-scale cold rolling mill is used to investigate the generation of wear debris in stainless steel. The influence of the hardness of the sheet, of the sheet surface finish before rolling, of the thickness reduction, and of the rolling lubricant temperature on the wear of the sheets due to cold rolling is investigated.

2. Methodology

Initially, pollution produced during industrial cold rolling of stainless steel sheets was collected from the lubricant filtration system (Fig. 1a). The filtration media in this system presents mesh of 2 μm and is able to retain 10 mg/l of residues under a lubricant flow of 4100 l/min at 40 °C. However, as the filtering media becomes impregnated with the pollution produced during rolling, particles smaller than 2 μm can also be collected. To separate the particles smaller than 2 μm, a subsequent selective filtration was carried out in laboratory using mesh sizes of 1 μm, 0.8 μm and 0.45 μm. After thorough cleaning with toluene and drying, solid particles were separated from the oil (Fig. 1b). The morphology of the solid particles was assessed using SEM and their chemical composition was analyzed using EDS and X-ray diffraction.

After the confirmation that the pollution found in industrial cold rolling was composed of a mixture of lubricant oil and of wear debris (see Section 3), laboratory cold rolling mills were used to assess the effect of rolling parameters on the generation wear debris during rolling. Two types of stainless steel were studied: ferritic, due to its low cost, and austenitic, for its great versatility of use.

Table 1
Chemical composition of the stainless steel sheets.

Steel	Type	%Cr	%Ni	%Nb	%Ti
304 H	Austenitic	18.28	8.01		
304D	Austenitic	18.11	9.73		
P430	Ferritic	16.13	0.17	0.35	
409	Ferritic	11.29	0.12		0.14