Initiation of Sticking During Hot Forging of Steel Plate Using Low-Speed Ring Compression Test

Abhinav Datir, Mousam Sharma

Department of Mechanical Engineering, Sagar Institutes of Science & Technology, (SISTec), Bhopal, RGTU University, Bhopal, India

ABSTRACT

Hot forging of steel is one of the most important steps in manufacturing process regarding surface quality of the product. Stabilised ferritic steels are widely used in automotive and cosmetic appliances but are also concerned by sticking phenomenon. These grades, having high dry corrosion and creep resistance, are enriched in specific chemical elements such as Cr, Nb or Ti, limiting also slab oxidation during hot forging. Nevertheless, the mastered oxidation of slab surface is a way to protect metal surface from direct contact with rolls. In order to better understand initiation of sticking, a first campaign was based on topography and rolls surface state wear analysis. This study revealed that sticking initiation is not due to the presence of roll scratches which depth is higher than oxide layer thickness. Indeed, the probability that roll scratches are deeper than oxide layer thickness is very low. In a second time, a pilot was designed, reproducing tribological conditions of a roll bite, to better understand mechanisms that initiate sticking. Keeping in mind the importance of rolls and slab surface state, this pilot is able to use specimen taking from industrial products, having the original oxide layer surface. This second study highlighted the major role of silicon oxides on scale adherence and the high heterogeneity of this scale layer in thickness and in chemical composition.

Keywords: Hot forging; steel; Sticking; Rolls; Roughness; Topography; Dry corrosion

I. INTRODUCTION

New ferritic steel grades are developed to improve the lifetime of steel parts subjected to high temperature and corrosive environments, such as exhaust lines of trucks and heavy vehicles [1]. Currently, exhaust lines are made with Nb and/or Ti stabilised ferritic stainless steels because fatigue, creep and corrosion resistance are known to be high for these materials, as exposed by Fujita et al. [2]. Nonetheless, the forming of high chromium ferritic steels is risky in terms of surface quality [3]. One of the major issues of the ferritic steels is that they are sticking to the tools because of their high chemical affinity with them. This phenomenon appears during the hot strip forging of the steel especially in the finishing mill, where the strip is rolled through seven stands going from 35 mm to 3 mm, in a few seconds. Jin et al. [6] and Son et al. [7] studied the influences forging process parameters (such as temperature, lubrication or reduction) on the sticking of steel product to the working roll by chemical adhesion. They performed

tests on the disc-on-disc tribometer described by Liu et al. [5].Assuming the oxide layer fracture is the initial step of the formation mechanism of sticking defect [4], they concluded that an initial scratch deeper than the oxide layer of the product has to exist on the working rolls to initiate the sticking.

When coming in contact with the strip, scratches break the oxide scale and direct contacts between the metal base and the metal of the rolls occur. So the main advantage of steels during its lifetime becomes a serious drawback during its forming: the high corrosion resistance of steels limits the formation of a thick oxide scale layer on the strip surface and, consequently, increases the risk of direct contact between working rolls and strips. Nevertheless, these conclusions rely on tests performed on specific specimens, with oxide scale layers created according to laboratory heating conditions that are strongly different from industrial ones. Consequently some specific oxide compounds created at very high temperature are not present on

specimen surfaces and may invalid the conclusion of that study.

The paper is divided in three parts. The first part presents a survey on roll roughness. The objective is to characterise scratches or macro-defects on roll surfaces that would initiate the breaking of product oxide layers. The second part is related to the development of a specific tribological test bench able to simulate industrial conditions of contact. A special attention is given to the ability of the bench to perform test on industrial oxidized surfaces. Finally, tests are performed on stainless steel specimens and the role temperature and reduction ration on the occurrence of surface defect is studied.

Hot forging test bench

The sticking material observed on the work roll derives from direct contact between the transfer bar and the rolls. This result highlights the key role of tribology on the "success" of the hot forging process. As a consequence, a perfect knowledge of the tribological behaviour of hot forging is required to understand the sticking occurrences in order to limit them. But it is well known that tribology implies complex phenomena and should be studied with great care in order to guaranty the reliability of the results [9]. So a specific test bench has been developed in order to analyse the initiation of material sticking from strip to work rolls (Fig. 4).Tests operate in two steps: a flat test piece is heated by induction to a temperature up to 1200°C, then the test piece is rolled between a pair of cylinders with a given thickness reduction. In order to respect the thermo-mechanical contact conditions, the thickness reduction of the bench, the exit speed of the test piece and the specimen temperature are adjusted to the industrial process ones. Consequently effective plastic strain, strain rate and contact pressures are in the same range as those of the process.

In order to respect the physic-chemical contact conditions:

- the flat specimens are machined from real bars so that one of the specimen surface correspond to the oxidized bar surface,
- the cylinders are machined from real working rolls and are grinding according to the same schedule as the industrial roll.

By respecting these recommendations, surfaces in contact on the bench have the same roughness, hardness, cleanliness, surface energy and oxidation as those of the process and they undergo the same thermal and mechanical loading. Direct test results are the normal and tangential forces on the cylinders and chemical and topological analyses performed on cylinders and test piece surfaces. The results are then expressed in terms of surface quality (mostly qualitative results) or in terms of friction identification (quantitative results) [11]. Coulomb's coefficients of friction are obtained by inverse identification from experimental normal and tangential forces.

Hot forging of steel and roll roughness analyses

In order to manufacture strips of steel, slabs of two meters wide, 0.2 m thick and 18 m long, which represent an average weight of 25 tons, are obtained from continuous casting. Then slabs are reheated during 3 hours up to temperatures around 1250 °C and are transformed into transfer bars by reducing their thickness from 200 mm to 40 mm in 5 to 7 successive passes in a roughing mill. Finally, bars are reheated through a thermal tunnel and their thickness is reduced to 3 mm on a 7 stands finishing mill. The temperature of transfer bars is around 1100°C at the entry of the finishing mill and decreases to 950°C at the exit (Fig. 1). The average oxide layer thickness resulting from this complex thermo mechanical history is around 30 and 50 μm after descaling. As sticking defects are mainly noticed at the end of the transformation process, the present study focusses on the finishing mill. In order to confirm the hypotheses of Jin et al. [6] on sticking initiation, roughness of cylinder are measured during production. Due to their large dimension direct 3D roughness measurements on cylinders were not possible. So replicas were made using the Repliset T3 resin (proposed by Struers®). A total of 112 replicas were done. Measurements were performed on upper and lower working rolls of each of the 7 stands of the finishing mill. For each roll, four zones were measured along the axial direction: at the centre, at 1.300 m, 1.5 m and 2.0 m from the border. Rolls were analysed after 50 km and after 500 km processing. On each replica, roughness measurements were performed at least 5 times on a 3D white light interferometer. Results were filtered and analysed with MesRug Expert System [8]. Scratches resulting from the grinding of the rolls clearly appear on surface roughness (the valley on Fig. 2). Nonetheless the maximal amplitude of the profiles Pz is obtained on the rolls of stand 4 and is lower than 25μm.

The average scratch depth is around 12 μm (Fig. 3). The average distance between two consecutives scratches is around 500μm, with a minimum equal to 420μm. The average width of the valley is around 30μm, with a minimum equal to 10μm. This campaign confirms that if scratches are the corresponding initiation sites for sticking phenomenon, the transfer bar oxide layer should be thinner than 25 μm and that the defect size should be smaller than 480 μm in diameter. As the transfer bar oxide layer is thicker than 40 μm, the hypothesis of roll scratch to be the initiation site of sticking phenomenon is seems very improbable.
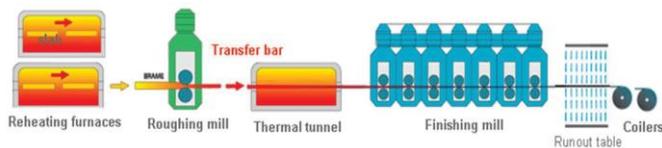
Figure 1. Transformation of a slab to a black coil
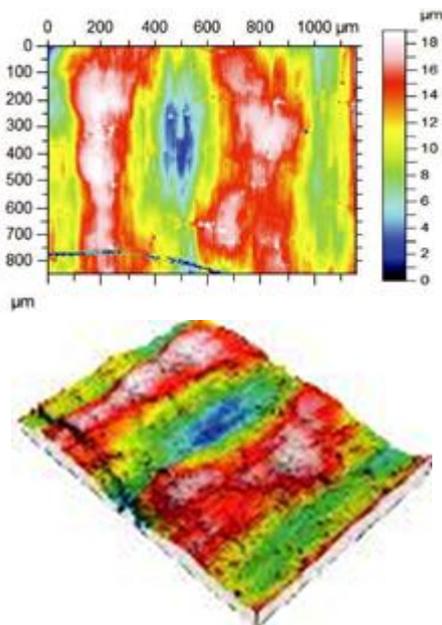
Figure 2. Example of 3D surface roughness.
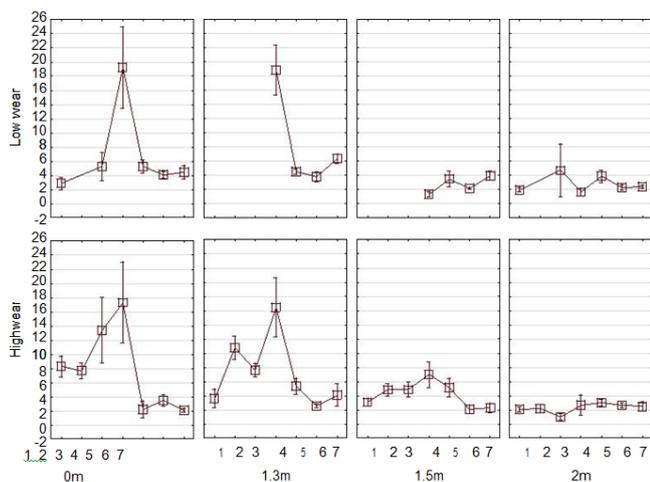
Figure 3. Pz value depending on stand number and wear rate (high wear = 500 km, low wear = 50 km).

Test results

Tests have been performed with forging temperatures ranging from 900°C up to 1100°C with increments of 50°C, and reduction ratios ranging from 20% to 40%, with increment of 10%. These correspond to the minimal and maximal values encountered on the finishing mill. No lubricant was used since the industrial process is not lubricated.

Coefficient of friction

Table 1 sums up the evolution of the Coulomb's coefficient of friction for each test configuration. On a general way, friction coefficient tends to increase with reduction ratio. But this trend is not completely true at 1050°C where coefficient of frictions identified at 30% and 40% of reduction seems to be confused. At 20% reduction, the friction coefficient is quite stable with temperature. A small increase of friction coefficient is noticed on the two last temperatures: 1050°C and 1100°C. At 30% reduction, friction coefficient tends to increase up to 1050°C and decreases at 1100°C. At 40% of reduction, friction is quite stable but decreases slightly with temperature. As a result, reduction ratio and temperature can have contradictory effects on friction coefficient. These results are the consequence of the variation of the behavior of the oxide scale at high temperature. A survey proposed by W. Jin pointed out the different behaviour of strip surface and slab surface, highlighting the specific effect of scale layer structure on friction (Fig.5) [12]. In a more recesnt work, D.J. Ha specified that friction of ferritic steel increases with temperature up to 1000°C, and decrease on higher temperatures due to the creation of Cr oxides on the product surface[13].

Oxide Scale Layer

Mean oxide scale thickness was measured after forging test (Table 2). Thickness after forging is ranging from 25 to more than 50 μm. No obvious connexion is noticed between friction and oxide thickness (Fig. 6). As oxide thickness is not the key parameter explaining friction coefficient variations, some investigations in scale layer morphology were performed in order to understand such changes. Surfaces deprived from oxide layer were noticed in the transversal direction of a high number of tested specimens. The minimal size of these plateaus is around 50 μm and the maximal size is around 900 μm. The average size equals 200 μm

(Tables 3 and 4). This dimension corresponds to the average size of the sticking defect observed on industrial strips. Observation of cylinders after the tests clearly showed that the oxide layers originally present specimen plateaus were transfer onto cylinder surface and are then explained by a lack of adherence of parts of the oxide scale (Fig. 7).The general evolution of density of plateau seems to be correlated to friction coefficient evolution, except for 40% reduction tests, and temperatures higher than 1050°C at 30% reduction. Plateaus are the contact area between roll and specimen, as a result, the wider the contact area, the higher the friction coefficient.

SEM-EDS analyses of the oxide layer after a reduction of 30% are presented on figure 8. The inner part of the oxide (close to steel substrate) essentially composed of $CrFe_2O_4$ and $FeCr_2O_4$ is present in all temperature case (from 950 °C to 1100 °C) and are very compact. The outer part of the oxide essentially composed of iron oxides (Fe_2O_3 and Fe_3O_4) tends to disappear on rolled specimen with increasing forging temperature. Iron oxide initially present at specimen surface seems to leave the specimen and play the role of a solid powder lubricant during forging. It could explain why, at high temperatures and high reduction rate friction coefficient is decreasing despite of increasing contact areas and plateaus size.

Figure 4. Design of the test bench [10].
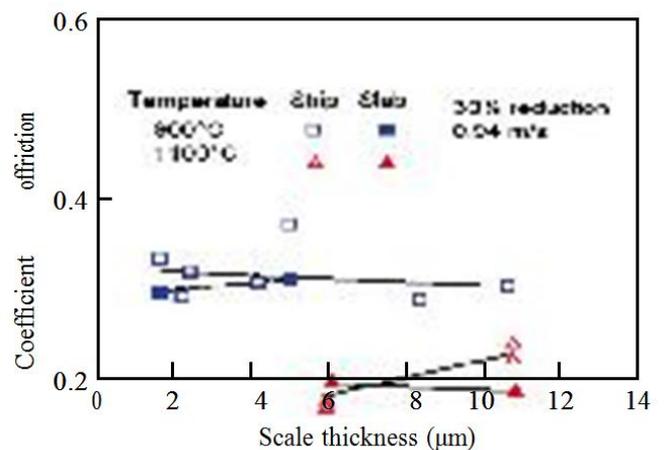
Figure 5. Evolution of friction coefficient with temperature and scale thickness according to Jin et al. [5].

Table 1. Value of Coulomb's coefficient of friction identify for each test condition.

Thickness reduction	forging temperature			
	950°C	1000°C	1050°C	1100°C
20%	0.14	20%	0.16	0.18
30%	0.19	30%	0.34	0.22
40%	0.31	40%	0.30	0.27

Table 2. Average oxide thickness measured on specimens after forging test.

Thickness reduction	forging temperature			
	950°C	1000°C	1050°C	1100°C
20%	36	25	40	36
30%	43	45	44	37
40%	53	38	45	28

Table 3. Average size of plateaus.

Density	950°C	1000°C	1050°C	1100°C
20%	1	2	2,3	0
30%	3,6	4,3	2	3,3
40%	x	5,3	3,6	9

Table 4. Density of plateaus on strip specimens

Size	950°C	1000°C	1050°C	1100°C
20%	313	506	588	0
30%	112	140	176	195
40%	X	171	278	202
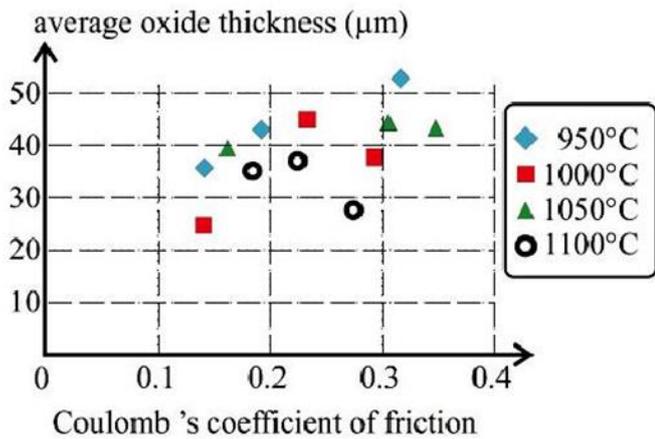
Figure 6. Evolution of oxide thickness with friction coefficient, temperature and reduction ratio.
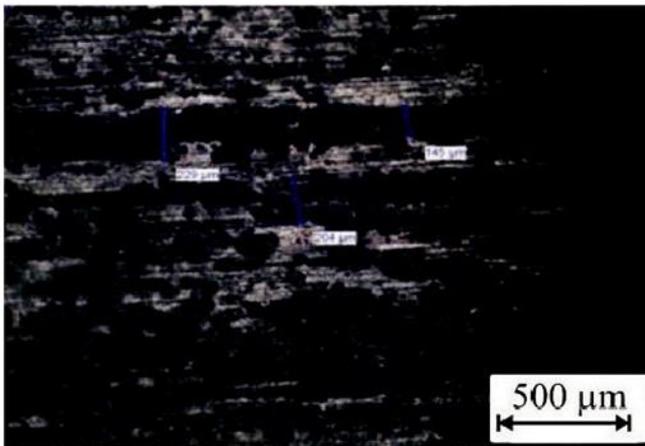
Figure 7. Cylinder surface after testing. Cylinder surface in grey, oxide layers transfer from specimen in black
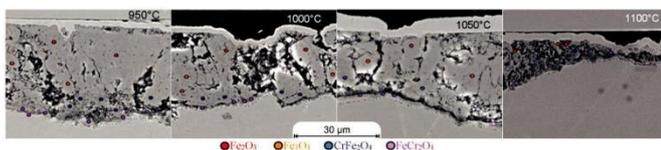
Figure 8. Evolution of oxide layer with temperature (after 30% reduction forging tests)

II. CONCLUSION

The sticking of ferritic steel onto working cylinders during hot forging has been investigated. Tests have been performed on a new hot forging testing bench at temperature in the range 950°C-1100°C and reduction ratio in the range 10-30%. Specimens were machined from industrial transfer bars in order to present a realistic industrial oxide layer. The assumption proposed by Son et al. stating that sticking occurs if scratches on cylinders are deeper than the oxide layer thickness on transfer bars has been invalidate. This condition may be sufficient but is not necessary. Test results show that the behaviour of the oxide layer play

an important role in the sticking occurrence. Two different mechanisms are observed. First, sticking can be initiated in zones where the oxide layer adherence on the transfer bar is wick. The oxide scale is than transfer to the work roll leading to the formation of plateaus where the first metal/metal contacts may occur. Friction is then increasing. Second, the transformation of oxides at high temperature leads to the migration to the surface of Fe2O3 and Fe3O4 where they play the role of a solid powder lubricant.

III. REFERENCES

[1]. P.O. Santacreu, A. Acher, 2011. Ferritic Steel Grade with Improved Durability for High Temperature Exhaust Manifold, SAE International, 2011-01-0194.

[2]. N. Fujita, K. Ohmura, M. Kikuchi, T. Suzuki, S. Funaki, I. Hiroshige, 1996. Effect of Nb on high-temperature properties for ferritic stainless steel, Scripta Materialia, 35, 6, 705-710.

[3]. W.E. Boggs, D.E. Sonon, 1978. Method for improving the surface quality of steels and other chromium iron alloys, US Patent 4, 078, 949.

[4]. W. Jin, J.Y. Choi, Y.Y Lee, 2000. Nucleation and growth process of sticking particles in ferritic stainless steel, ISIJ International, 789-793.

[5]. C.Y Son, C.K. Kim, DJ. Ha, S. Lee, J.S. Lee, K.T. Kim, Y.D. Lee, 2007. Mechanisms of sticking phenomenon occuring during hot forging of two ferritic stainless steels, Metallurgical and materials transactions A, 2776-2787.

[6]. J.X. Liu, Y.J. Zhang, J.T. Han, 2010. Test research on sticking mechanism during hot rolling of SUS 430 ferritic stainless steel, International Journal of Minerals, Metallurgy and Materials, 573-578.

[7]. S. Lee, D. Suh, S. Oh, W. Jin, 1998. Sticking mechanism during hot rolling of two stainless steels, Metallurgical and materials transactions A, 696-702.

[8]. M. Bigerelle, G. Guillemot, Z. Khawaja, M. El Mansori, J. Antoni, 2013. Relevance of Wavelet Shape Selection in a complex Mechanical Systems and Signal Processing, 41, 1–2, 14-33.

[9]. J.A. Schey, 1983. Tribology In Metals Working, Friction, Lubrication and Wear, American Society for Metal, Metals Park, Ohio, USA.

[10]. E Luc, M. Dubar, A. Dubois, A. Hermant, J-M. Damasse, Dubar L., 2012. Study of tribological

oxide layer behaviour during the hot rolling of ferritic stainless steels, proceeding of the 30th Journées Sidérurgiques Internationales, Paris.

[11]. E. Daouben, A. Dubois, M. Dubar, L. Dubar L., R. Deltombe, N. Truong dinh, L. Lazzarotto, 2008. Effects of lubricant and lubrication parameters on friction during hot steel forging. International Journal of Material Forming, 1, 1223-1226.

[12]. W. Jin, D. Piereder, J.G. Lenard, 2002. A study of the coefficient of friction during hot rolling of a ferritic stainless steel, Lubrication Engineering, 58, 29–37.

[13]. DJ. Ha, CY. Son, JW. Park, JS. Lee, YD. Lee, S. Lee, 2008. Effects of high temperature hardness and oxidation on sticking phenomena occurring during hot rolling of two 430 J1L ferritic stainless steels, Materials science and engineering A, 492, 49-59