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Overview of friction modelling in metal forming processes

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Abstract

In metal forming processes, friction between tool and workpiece is an important parameter influencing the material flow, surface quality and tool life. Theoretical models of friction in metal forming are based on analysis of the real contact area in tool-workpiece interfaces. Several research groups have studied and modelled the asperity flattening of workpiece material against tool surface in dry contact or in contact interfaces with only thin layers of lubrication with the aim to improve understanding of friction in metal forming. This paper aims at giving a review of the most important contributions during the last 80 years covering experimental techniques, upper bound solutions, slip-line analyses and numerical simulations. Each of the contributions shed light on the importance of the real contact area and the influencing parameters including the material properties, surface conditions, normal pressure, sliding length and speed, temperature changes, friction on the flattened plateaus and deformation of the underlying material. The review illustrates the development in the understanding of asperity flattening and the methods of analysis. Finally, the present paper discusses the necessary future work in order to advance further in modelling of real contact area in relation to implementation of frictional conditions existing finite element codes for simulation of metal forming processes.

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Keywords: Metal forming tribology; Asperity flattening; Real contact area.

1. Introduction

The adhesion theory was the first quantitative theory on friction, which was proposed independently by three different research teams around 1940; namely Holm [1], Ernst and Merchant [2] and Bowden and Tabor [3]. The theory was based on analyzing the individual plastic deformation of contacting asperities between two metal surfaces

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and shearing due to adhesion and cold welding of the asperities. Bowden and Tabor observed that the linearity between normal pressure and friction in Amontons-Coulomb's model disappears when the normal pressure becomes large. A solution to this problem was proposed by Orowan [4] in modelling of rolling by applying the shear flow stress as an upper limit. The present paper aims at providing a concise summary of the most important contributions since these early findings until the present state of the art of friction modelling in metal forming.

2. Contributions before 1970

Following the theory of friction based on asperity contact by Bowden and Tabor [3], research was intensified in understanding what happens in the junctions at the asperity contacts and how the real area of contact develops. Based on slip-line analysis, Green [5,6] studied the stress fields associated with different wedge shaped joints. Fig. 1a shows an illustration of a joint and an example of one of Green's slip-line fields. Both strong and weak joints were analyzed and experimental validation of the assumed deformation fields was provided by relative movement between wedges of plasticine and mild steel. In analysis of junction growth upon relative sliding, Tabor [7] extended the theory of asperity flattening to include the increase of real contact area due to reduction of the yield pressure by the imposed shear stress upon relative sliding.

Shaw et al. [8] discussed the development of the real area of contact in metal forming processes and suggested a smooth transition between the already accepted linear increase at low normal pressures and full contact area at high normal pressures. The same transition applies for the frictional stress between tool and workpiece. Shaw et al. [8] provided experimental evidence for the smooth transition by a modified Brinell hardness test. The transition can be attributed to subsurface deformation and interaction between the deformation fields of the asperities. It was already mentioned by Bowden and Tabor [3] that friction cannot be regarded as a pure surface effect because plastic bulk deformation influences the formation of contact area. Additional weight to this statement was later given by Greenwood and Rowe [9] and Fogg [10]. Greenwood and Rowe [9] showed experimentally by compression tests of cylinders with different height to diameter ratios that asperity flattening increases with surface expansion. Fogg [10] showed experimentally that bulk straining results in larger contact area at constant nominal normal pressure in an apparatus illustrated in Fig. 1b. Fogg explained it by the tangential tensile stresses reducing the yield pressure necessary to flatten the asperities similar to the effect of shear stress as explained by Tabor [7]. The study by Fogg had focus on stretch forming, where the sheet material experiences elongation at normal pressures not resulting in full contact area. The reduction of yield pressure was supported by analysis of effective hardness under different tangential loading, e.g. under biaxial stretching at the bottom of a deep drawing operation.

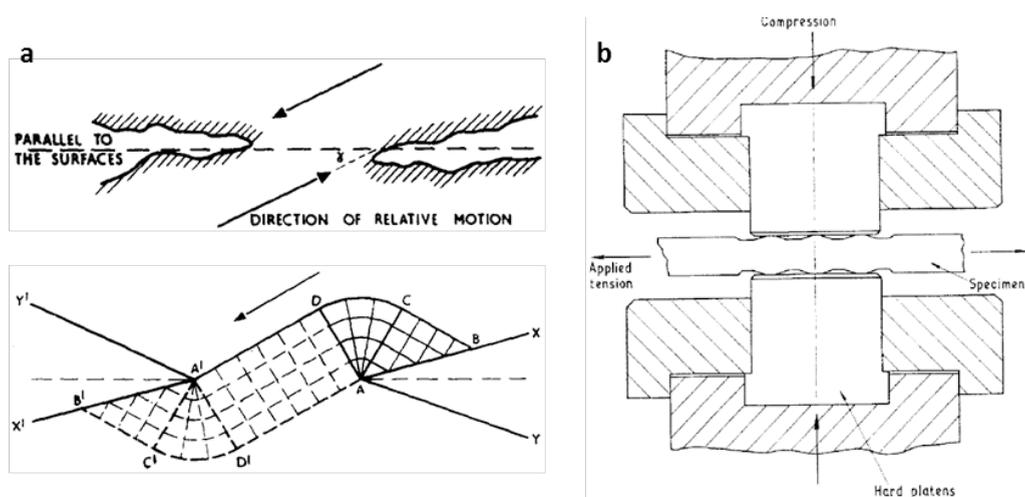


Fig. 1. Illustrations of (a) strong junction in relative sliding and the associated slip-line field by Green [5] for theoretical analysis; (b) compression of asperities under tangential tensile loading by Fogg [10].

3. Contributions in the 1970s

A great deal of the research in the 1970s was focused on theoretical determination of the real contact area at high normal pressures, where individual asperity deformation no longer prevails. A common assumption was to neglect bulk deformation except for the subsurface layers, where interaction between asperities takes place. Pullen and Williamson [11] stated a lower bound to the real area of contact by simple analytical assumptions to the asperity deformation. The analytical expression was in good agreement with their experimental results over a wide range of normal pressures covering the transition zone. The chosen dimensionless representation, however, leaves practical use difficult as the non-dimensional load is not easily measured. Wanheim [12] suggested a slip-line solution inspired by plane strain extrusion for theoretical calculation of the real contact area from low to high normal pressures and presented validating experiments. Wanheim et al. [13] extended the slip-line solution to account for frictional sliding (Fig. 2a) and presented real contact area (Fig. 2b) and frictional stress (Fig. 2c) as function of normal pressure for different amounts of friction on the flattened plateaus. The friction stress was assumed proportional to the real contact area ratio and the shear flow stress with the proportionality factor being the friction factor between tool and workpiece in the real contact. The resulting front and rear flank angles due to frictional sliding and their effects on the real area of contact was accounted for by Bay and Wanheim [14], the effect of asperities on asperities was analyzed by Steffensen and Wanheim [15], and the effect of trapped lubricant and average strain hardening were accounted for in Wanheim and Bay [16], where the resulting surface roughness was also predicted. At the end of the decade, Challen and Oxley [17] proposed three slip-line models accounting for rubbing, wear and cutting and predicted on this bases the three regimes of asperity deformation depending on the asperity angle between a hard and a soft asperity and their mutual friction factor.

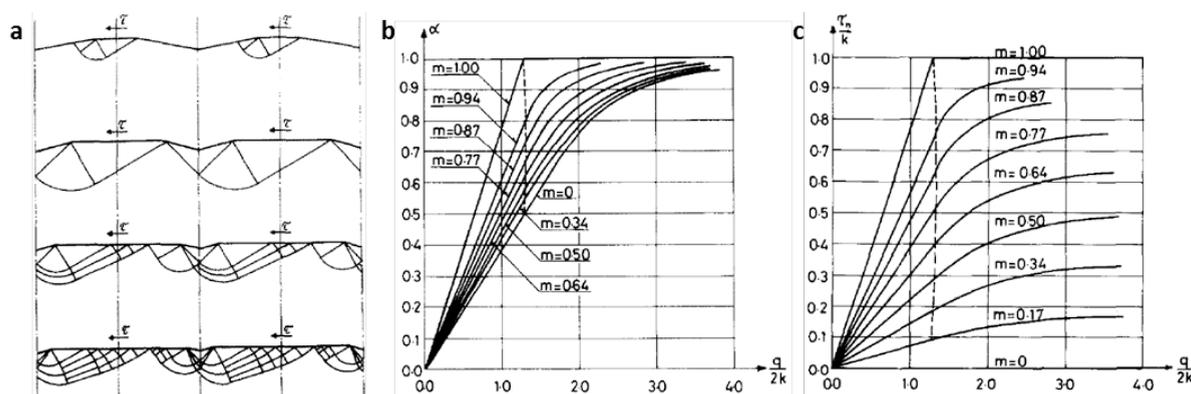


Fig. 2. Illustrations by Wanheim et al. [13] showing slip-line fields of (a) plane extrusion through a smooth square die giving inspiration to modeling of asperities; (b) proposed slip-line field for asperity flattening under frictional sliding; (c) theoretical real contact area for different amounts of friction on the flattened plateaus as function of normal pressure.

4. Contributions in the 1980s

At the threshold of the 1980s, Wanheim and Abildgaard [18] suggested plastic waves as a mechanism for friction and gave by a slip-line analysis the influence on apparent friction. Luo et al. [19] studied the plastic wave phenomena by upper bound solutions, and Bin and Luo [20] applied the emerging FEM in their study to predict strain distributions and apparent friction. These groups also proved the existence of the phenomena by experiments. Challen et al. [21,22] studied by slip-line analyses and experiments the relative sliding between a hard tool with wedge shaped grooves and a soft material. The development of the filling of the hard tool and the transition between plastic waves and wear were studied.

Asperity flattening was still a main research topic due to the lack of theoretical modeling involving bulk deformation besides the interaction between asperities. Sheu and Wilson [23] presented an upper bound solution for the asperity flattening under bulk deformation by analogy with flat hardness indentations. Later refinements of the

upper bound solution [24] allowed matching with rolling experiments. Sutcliffe [25] suggested the slip-line field in Fig. 3a for theoretical determination of the real contact area in asperity flattening under bulk deformation. The slip-line field consists of the combination of the slip-line fields for indentation and uniform deformation. Solution of the field together with geometrical consideration of triangular asperities resulted in a differential equation for the real contact area as function of normal pressure, longitudinal strain and flank angle. Fig. 3b shows the resulting set of curves for flank angles of 20° . Makinouchi et al. [26] simulated asperity flattening by an FE model including three asperities with free sides, where strain hardening was included in the analysis. Ike and Makinouchi [27] extended the model to include five asperities and also presented a single asperity with periodic boundary conditions. They were able to analyze different levels of subsurface deformation with their models.

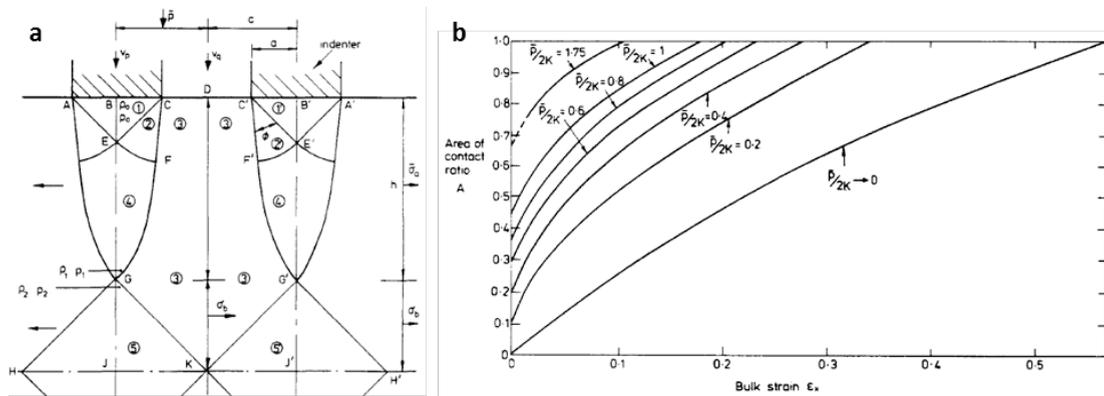


Fig. 3. Illustrations by Sutcliffe [25] showing (a) a combined slip-line field for hardness indenters and uniform deformation for theoretical analysis of asperity flattening with subsurface deformation; (b) resulting contact area ratio for different normal pressures as function of longitudinal bulk strain with asperity flank angles of 20° .

5. Contributions in the 1990s

Wilson [28] extended the use of previous work [23,24] to include more complex surface contact including a rough tool in relative sliding with a softer workpiece material, and Korzekwa et al. [29] applied numerical modeling by FEM to simulate asperity deformation under bulk deformation. They analyzed the influence of different straining directions relative to the direction of the long 2D asperities. They additionally showed the possibility of simulating asperity flattening with a 3D layout of asperities. Saha and Wilson [30] presented experimental results from a friction test, where the workpiece strip material is simultaneously under normal pressure and in-plane elongation. Depending on the strip material, they experienced both increasing and decreasing friction with increasing elongation, and they explained it by dominant asperity flattening in the former case and dominant roughening due to coarse grains in the latter case. A new view of friction modeling was presented by Carter [31], who suggested that the modeling should be based on the deviatoric component of the interfacial normal pressure rather than the total normal pressure which was commonly used and still is. Carter's argument was that when the plastic deformation itself is independent of the hydrostatic pressure, the friction modelling by the adhesion theory should also be independent of the hydrostatic pressure. At the end of the decade, Sutcliffe [32] proposed theoretical modelling of asperity flattening under bulk deformation taking into account different wavelength of the asperities. Sutcliffe was able to calculate the real area of contact as well as the changing roughness based on a model with asperities with two different wavelengths and validated the predictions by experiments.

6. Contributions since 2000

Developments of numerical algorithms during the past decades made the use of numerical simulations continuously growing since the turn of the millennium. Zhang et al. [33] demonstrated numerical simulation of local tool-workpiece contact to establish a local friction model based on specific tool and workpiece roughnesses and

applied the model in simulation of deep drawing. Hol et al. [34,35] presented multi-scale simulation of the frictional effects in sheet metal forming. Local friction coefficients were estimated based on the real surface topographies through analytical expressions taking in the statistical surface parameters. Asperity flattening under normal as well as tangential loading was included along with the local material flow near rough tool surfaces. The local information on friction coefficients were then supplied to a full scale simulation of deep drawing. Wang et al. [36] presented a testing apparatus capable of flatten asperities under bulk deformation. They also showed numerical simulation of their five-asperity test with an example of the resulting real contact area as function of effective bulk plastic strain (Fig. 4a). They proposed a new friction model as shown in Fig. 4b, where a critical normal pressure separates the two regimes defined by Amontons-Coulomb's model at low normal pressures and the constant friction law at high normal pressures. They provide an expression for the critical pressure and suggest an expression linking the friction coefficient μ and the friction factor m , such that it is enough to estimate the friction coefficient at low pressures for determining the full friction model. They take into account the fact that the flattened asperities are not in full contact with the tool due to higher order real contact areas as described by Steffensen and Wanheim [15]. In a later contribution, Wang et al. [37] included strain hardening in their analysis of asperity flattening. Nielsen et al. [38] focused on determining the real contact area ratio as function of normal pressure and longitudinal bulk strain for strain hardening materials by experiments and FE simulations. Results for aluminum 1050 are shown in Fig. 4c.

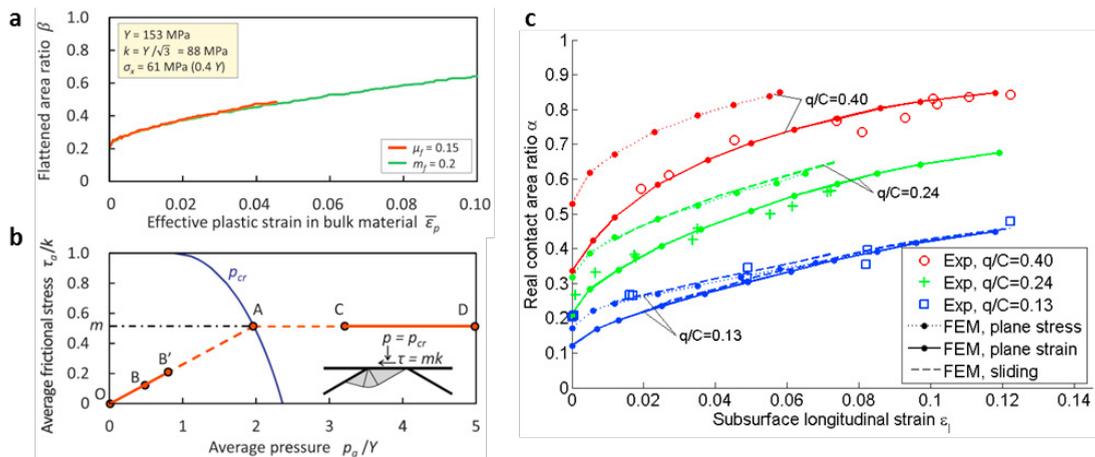


Fig. 4. (a) Simulated real contact area as function of effective strain by Wang et al. [36]; (b) Friction law by Wang et al. [36]; (c) Simulated and experimental real area of contact at different normal pressures as function of subsurface longitudinal strain by Nielsen et al. [38].

7. Conclusions and possible future work

Having presented a subjective overview of the most important contributions to friction modeling over the last 80 years, it seems to be necessary to still work on full mapping of the real contact area as function of normal pressure, bulk deformation, material properties and surface conditions. It is also necessary to work closer to the real sizes of asperities rather than model asperities, and finally, it is expected that existing FE codes will more commonly be enhanced by new developments of friction modeling in the future.

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