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Size effects in micro rolling of metals

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Abstract. Size effects are a unique characteristic with miniaturisation, and may cause a number of unexpected problems in micro rolling of metals in the aspects of mechanical behaviour, tribology, and scatter of material behaviour. This paper has introduced three kinds of micro rolling technologies, including micro ultrathin strip rolling, micro flexible rolling and micro cross wedge rolling, and analysed the size effects appeared in each of the micro rolling process. This paper will be helpful for understanding the problem of size effects, and can contribute to the manufacturing of high quality micro metallic products by minimising the impact of size effects in micro rolling with optimised processing parameters.

1. Introduction

Product miniaturisation, which aims to reduce product weight, volume, cost and pollution, is a global trend for facilitating product usage and enabling product functions to be implemented in microscale geometries. Increased demands for miniaturised products have greatly accelerated the development of microforming technology, one of the most popular micromanufacturing processes for the fabrication of very small metallic parts in the submillimeter range [1]. The fabricated micro products have tremendous applications in diverse areas including micro-electromechanical systems (MEMS), micro fluidics systems (MFS), medical devices, precision equipment, and communication devices. Microforming is applicable to a wide range of materials, and can be used to economically fabricate metallic micro products with complex geometries, excellent dimensional tolerances, required mechanical properties and improved surface quality [2].

In metalworking, rolling is metal forming process in which workpiece is passed through one or more pairs of rolls or featured tools to reduce the thickness or to form specifically shaped products. Micro rolling, as the name suggests, is one of the microforming methods. In micro rolling, the dimensions of workpiece along the deformation direction are in the submillimeter range, and the rolling deformation is processed in microscale. Traditionally, micro rolling refers to micro ultrathin strip rolling by which small and ultrathin strip is flat-rolled to reduce the thickness and to make the thickness uniform. In micro ultrathin strip rolling, the width and thickness of the strip being rolled are normally in the domains of lower millimetre and submillimetre, respectively. With the development of rolling and microforming technology, other micro rolling methods, including micro flexible rolling [3, 4] and micro cross wedge rolling [5], have also been successfully developed.

Micro rolling can be employed to manufacture net-shape or near net-shape micro products with high quality. One direct way to realise micro rolling process is by scaling down the rolling system from the macroscopic to the mesoscopic domain. Unfortunately, rolling theories and technologies established in the macro world cannot be simply scaled down to the micro world, because it is

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impossible to scale down all parameters in the micro rolling process according to the theory of similarity due to the size effects which are well known as a unique characteristic with miniaturisation. Size effects occur due to the fact that the ratio among all decisive features cannot be kept a constant according to the process requirements, and may cause a number of unexpected problems in micro rolling process in the aspects of mechanical behaviour, tribology, and scatter of material behaviour. Therefore, the size effects in micro rolling have to be identified in order to manufacture high quality micro products that meet the high demands.

This paper aims to characterise the size effects in micro rolling of metals. In the following sections, three micro rolling technologies, including micro ultrathin strip rolling, micro flexible rolling and micro cross wedge rolling (MCWR), will be respectively introduced followed by an analysis on the size effects appeared in each of the micro rolling process.

2. Size effects in micro ultrathin strip rolling

Ultrathin strip manufactured by micro rolling has a wide application in electronic and instrument industries, and its production has always been of interest to the manufacturers and researchers in the area of metal rolling. The principle of micro ultrathin strip rolling is the same as that of conventional flat rolling, and the rolling process can be schematically illustrated in Figure 1. Differently, the deformation of ultrathin strip in micro rolling is affected by size effects.

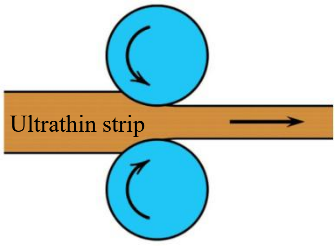

Figure 1. Schematic illustration of micro ultrathin strip rolling.

With miniaturisation of the rolled ultrathin strip, the ratio of grain size to the characteristic dimension will be changed. When the strip's thickness is kept constant but the grain size is increased, the yield strength of the strip will be decreased according to the Hall-Petch effect [6, 7]. Similarly, the yield strength will also be reduced when the strip's grain size is kept unchanged but the thickness is reduced based on the surface layer model [2]. The above both cases may lead to reduced flow stress in rolling. With increasing the grain size or reducing the strip's thickness, the number of grains through the thickness becomes so small that the strip's behaviour will be characterised by only a few grains. As the grains possess different sizes, shapes and orientations, each grain will play a significant role in plastic deformation in micro ultrathin strip rolling.

The coefficient of friction (COF) will increase with miniaturisation in micro ultrathin strip rolling. An increase in COF induces increased rolling force, intermediate force and edge contact force. The work roll edge contact can increase work roll edge wear, which will shorten the work roll service life. The strip profile can be improved when the COF increases [8]. The edge kiss of work rolls can also improve the strip shape when no work roll bending force is applied. The edge kiss force between the two work rolls will increase when the COF increases, which can improve the shape of ultrathin strip in rolling [9]. When suitable friction conditions along the longitudinal and transverse directions are applied to the micro rolling process, a good shape and profile of ultrathin strip can be obtained [10]. Surface roughness affects the friction behaviour, stress distribution, and surface quality, which will become more significant with the scaling down of strip's thickness. The surface roughness will decrease with an increase in pass reduction due to the reprinting or interaction between the rolls and the rolled ultrathin strip.

In micro ultrathin strip rolling, lubrication plays an important role in the cooling of rolled material, reducing of rolling force, decreasing of wear of both rolls and rolled material, and lowering of friction. When oil-based lubricant is applied to micro ultrathin strip rolling, the oil film thickness decreases with the increase of pass reduction and the decrease of rolling speed. When the oil film thickness is increased, rolling force will be reduced, the surface of the product, however, will become dull. Lubricating condition is remarkably influenced by roll-coating formation, especially by using smooth surface of rolls. For micro ultrathin strip rolling, the most preferable lubricant is emulsion [11]. The size effects on lubricant friction behaviour can be explained by the model of open and closed lubricant pockets, also known as dynamic and static lubricant pockets, respectively. Downscaling affects the ratio of open to closed lubricant pockets. As the topography is not scaled down with geometrical similarity, there will be a region of constant width where open lubricant pockets become effects. The open lubricant pockets have a connection to the edge of the surface and cannot keep the lubricant. When scaling down the strip's size, the contact area in rolling is reduced while the size of single topography features remains approximately constant, leading to increased ratio of open lubricant pockets. As a result, the friction and rolling force will increase in micro ultrathin strip rolling as compared to the conventional rolling process.

3. Size effects in micro flexible rolling

Micro flexible rolling is a novel microforming method for the production of ultrathin strip with longitudinal thickness variation. In micro flexible rolling, a gap control system is applied to adjust the roll gap online deliberately during rolling operations, and to manufacture the thickness transition along the rolling direction, as schematically illustrated in Figure 2. For achieving periodical changes in the roll gap, the top and bottom work rolls can move simultaneously in opposite directions, or only the top work roll moves, along the normal direction of the rolled strip. Adjustment of roll gap by vertical movement of the top work roll is commonly found in micro flexible rolling of metals [3].

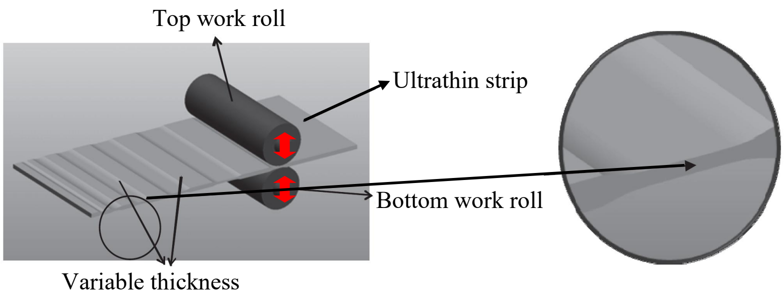

Figure 2. Schematic illustration of micro flexible rolling.

Micro flexible rolling differs from conventional flexible rolling because size effects that characterise the micro world are involved in the micro flexible rolling process. Significant springback problem occurs during micro flexible rolling process due to size effects, which has a great impact on the rolled products. In conventional flexible rolling, springback is negligible due to the absence of size effects, and the quality of the rolled sheets can be well controlled [12]. In micro flexible rolling, however, even a small springback of the rolled strip may cause big problem of dimensional accuracy due to the small deformation of ultrathin strip and the high requirement of dimensional tolerance. It is found that the average springback shows a decreasing trend with the increase of front and back tensions in case of micro flexible rolling of ultrathin aluminium alloy strips. For strips with thickness values of 100, 250 and 500 μm, more front and back tensions play a more crucial role in eliminating the springback despite the change of reduction [4].

The ratio of strip's thickness (T) to grain size (D) has a great effect on springback during micro flexible rolling. The ratio (T/D) decreases with scaling down the strip's thickness or increasing the grain size of ultrathin strip that has a constant thickness. In micro flexible rolling, the decrease of strip's thickness or the increase of grain size will result in a big springback, and the scatter of springback will become more serious with the decrease of T/D. This is because the grain number in the thickness direction drops due to the decrease of T/D, and the springback depends mainly on the mechanical behaviour of these limited grains. When the value of T/D increases, the effect of a single grain on the springback becomes small. As the springback of strip and the scatter of springback are reduced with the increase of T/D, high accuracy ultrathin strip with varying thickness can be successfully manufactured by micro flexible rolling method [2]. It should be noted that the degree of springback for different kinds of materials, such as steels, aluminium alloys and copper alloys, is different due to the difference in mechanical properties of the materials. Therefore, the springback that is caused by size effects should be identified specifically in the micro flexible rolling of different materials.

Ultrathin strip with varying thickness and perfect shape, flatness and optimal thickness transition length has wide applications in manufacturing industry. As a novel microforming method, micro flexible rolling is still under development. As the thickness of workpiece in micro flexible rolling is in the submillimeter range, reduction will become difficult due to the existence of a limit on the thickness of workpiece which can be reduced on a given mill. This minimum gage phenomenon is the result of a complex interaction of effects between the rolls and the strip rather than a function of the strip behaviour or of the mill behaviour along [13]. As a result, control of the reduction of the transition length of the varying strip thickness zone, and as well as the strip shape, profile, and flatness for thin strip, will be challenges for researchers and manufacturers in micro flexible rolling. This requires development of advanced micro flexible rolling equipment with high stiffness rolls and high-precision control system that have the capacity to minimise the impact of size effects and realise rapid dynamic response to change the roll gap and roll speed when the rolling mill is running.

4. Size effects in micro cross wedge rolling

Cross wedge rolling (CWR) is a metal forming technology in which a cylindrical rod is plastically deformed into an axisymmetrical part by the action of wedge-shaped dies moving tangentially relative to the workpiece. Conventionally, CWR is an efficient metal forming technology applied mainly for the manufacturing of stepped axles and shafts, and has been proven to be an economical and reproducible means of producing preforms for forging operations. CWR has three key features, including higher productivity, higher material utilisation and better working environment, as compared to other forming methods. MCWR technology derives from the concept of CWR, with CWR being scaled down into the micro domain. There are generally five different variants of CWRs in which two or three wedges mounted on rolls or flat or concave plates of rolling mills are used [14]. In MCWR, flat wedges are widely used due to its fewer requirements for sophisticated tooling structures so that tool manufacturing is much easier compared to other kinds of wedges, such as two-roll wedges, three-roll wedges and two concave wedges etc. Figure 3(a) shows an example of stepped shaft micro product manufactured by MCWR technology with a pair of flat wedges that are made of tool steel (Figure 3(b)).

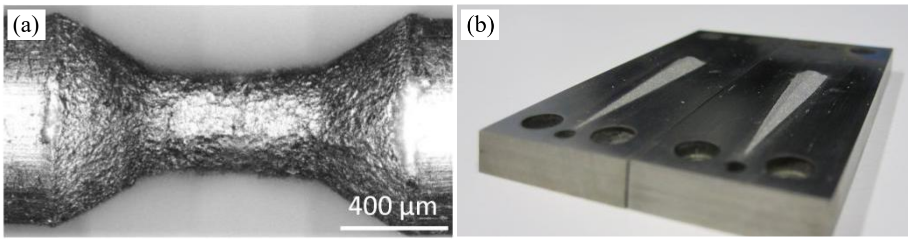

Figure 3. (a) Stepped shaft micro product manufactured by MCWR with (b) a pair of flat wedges.

Figure 4 schematically illustrates the MCWR forming process by using flat wedges, in which cross sections in five rolling stages have been shown: (I) knifing zone, (II) guiding zone, (III) stretching zone, (IV) sizing zone, and (V) unloading zone [15]. Wedges first cut into workpiece in its middle part and then, the V-shaped groove is generated along the entire circumference after the guiding zone. Subsequently, in the stretching zone the reduction of cross section is developed to the required width. Finally the geometrical dimensions of workpiece are refined during the sizing zone. The details of MCWR, including equipment, tools and process can be found elsewhere [2].

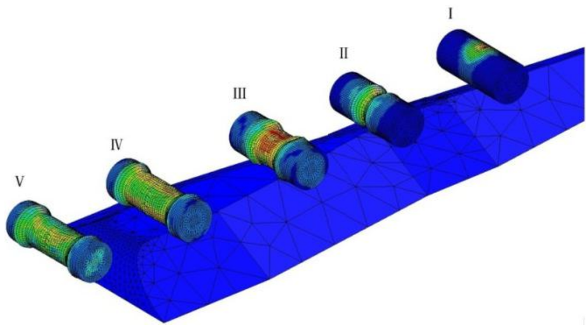

Figure 4. Schematic illustration of MCWR process consisting of five stages.

The original diameter of cylindrical rod being rolled in MCWR is generally in the submillimetre range. As a common problem in microforming, size effects also take place in the MCWR process of metals. Size effects have significant impact on the processing factors in MCWR, for instance, springback and surface topology of workpiece. In MCWR, the springback behaviour is related to the material's microstructure and deformation amount. The springback along both the axial and redial directions of manufactured product by MCWR as well as the springback scatter exhibit an increasing trend with the increase of grain size. Grain size has great effect on the strain and stress distribution of the workpiece processed by MCWR. Figure 5 shows the cross sections located in the middle of the cylindrical rods when rolling deformation of the rods is in the guiding stage (stage II illustrated in Figure 4). It can be seen that the continuous laminar distribution of stress and strain in the workpiece has been more significantly disturbed due to inhomogeneous mechanical properties with an increase of grain size.

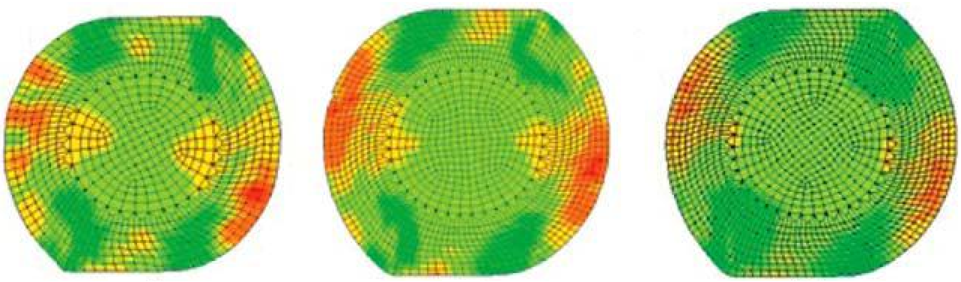

Figure 5. von Mises stress distribution on middle cross section of MCWR-processed workpieces with different grain sizes: (a) 248 μm, (b) 40 μm, and (c) 6 μm [15].

The springback of workpiece will become more significantly when the area reduction increases in MCWR. This is because that with the increase of rolling deformation, strain penetrates more deeply into the grains, resulting in activation of more dislocations and intertwinement of repelling dislocations which will release more inelastic springback in the unloading stage. Also, with miniaturisation, the relative ratio of the surface asperities of tools and blanks to the outside dimensions of workpiece becomes larger than that in the case of conventional macroscale process. As a result, the surface asperities may affect the frictional behaviour during MCWR process, and the processing characteristics and accuracy of the manufactured micro products [2].

In the presence of size effects, the distribution and evolution of strain and stress will become irregular in the processing of MCWR due to grain heterogeneity, which will induce inhomogeneous deformation. A homogeneous phenomenon of deformability of workpiece could be achieved at elevated temperatures, which could mitigate size effects and in turn lead to improvements in the edge quality of the products manufactured by MCWR due to the activation of more slip systems with thermal activation [5]. In order to take full advantage of MCWR technology, comprehensive investigations on the influence of miniaturisation, especially size effects, on process, accuracy control, and product quality are still needed.

5. Conclusions

Micro rolling is one of the microforming methods, and has been under prompt development with the global trend towards miniaturisation in diverse areas. In this paper, three micro rolling technologies, including micro ultrathin strip rolling, micro flexible rolling and micro cross wedge rolling, have been introduced, and the size effects appeared in each of the micro rolling process have been analysed. Size effects characterise the micro world, and have significant impact on material behaviour in micro rolling and the quality of rolled products. Through understanding the mechanisms of size effects and proposing appropriate control strategies, high-quality micro metallic products can be successfully manufactured by using micro rolling technologies with optimised processing parameters.

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