Faculty of Engineering and Information Sciences - Papers: Part A

Faculty of Engineering and Information Sciences

1-1-2013

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In this paper, a survey of four relatively recent rolling technologies is presented. The merits and drawbacks of each technique are examined. These techniques are: (1) Heated Roll Rolling, and the suitability of this technique for magnesium sheet production; (2) Asymmetric Cryorolling, which has potential for large-scale industrial production of nanostructural materials; (3) Variable-Gauge Rolling, used for production of flat products with variable thicknesses; and (4) Through-width Vibration Rolling, used for fabrication of ultrafine material sheets. Where possible, computer simulations of the rolling processes are described. Among the interesting simulation results obtained is the finding that the shear strain distribution in strips produced using the Through-width Vibration Rolling technology is more uniform and shows higher shear strain values, when compared with the conventional rolling technology.

Keywords

technologies, flat, rolling, recent, developments

Disciplines

Engineering | Science and Technology Studies

Publication Details

Yu, H., Lu, C., Tieu, A. Kiet. & Godbole, A. (2013). Recent developments in flat rolling technologies. In F. D.S. Marquis (Eds.), PRICM: 8 Pacific Rim International Congress on Advanced Materials and Processing (pp. 2139-2146). Hoboken, United States: Wiley.

RECENT DEVELOPMENTS IN FLAT ROLLING TECHNOLOGIES

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Keywords: Heated roll rolling, Asymmetric cryorolling, Variable gauge rolling, Through-width vibration rolling

Abstract

In this paper, a survey of four relatively recent rolling technologies is presented. The merits and drawbacks of each technique are examined. These techniques are: (1) Heated Roll Rolling, and the suitability of this technique for magnesium sheet production; (2) Asymmetric Cryorolling, which has potential for large-scale industrial production of nanostructural materials; (3) Variable-Gauge Rolling, used for production of flat products with variable thicknesses; and (4) Through-width Vibration Rolling, used for fabrication of ultrafine material sheets. Where possible, computer simulations of the rolling processes are described. Among the interesting simulation results obtained is the finding that the shear strain distribution in strips produced using the Through-width Vibration Rolling technology is more uniform and shows higher shear strain values, when compared with the conventional rolling technology.

Introduction

In 2012, the global crude steel production reached 1.54 billion tons [1]. This implies the worldwide use of a large number of processing methods for materials in general, and steel in particular. These processing methods include casting, forging, welding, etc. However, it is also seen that more than 70% metal products are produced by rolling in one form or another. This points to the great importance of rolling technologies used for metal forming.

Fig. 1 [2] shows a conventional hot rolling process as currently used for production of continuous-casting of slabs. The slabs are heated to more than 1100°C in furnaces, before they pass through a roughing mill and a finishing mill. This is followed by cooling, before the finished hot-rolled product is obtained.

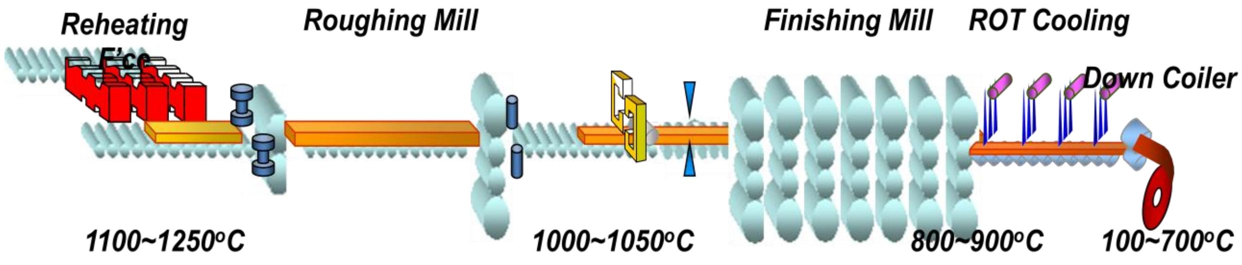

Fig. 1 Conventional hot rolling process

Some products produced by the conventional hot rolling process can be used directly, while some others are subjected to cold rolling before being used. In any rolling process, monitoring

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the geometrical shape of the product is of primary importance. For example, it is important to check whether the products have an edge wave, central wave. Secondly, we need to monitor the defects such as surface cracks, edge cracks. Thirdly, we need to monitor the microstructure, because it is the microstructure that determines the mechanical properties of product. In order to ensure effective monitoring of these three aspects, we need to control the rolling temperature, rolling schedule, roll wear and lubrication, etc. In brief, the (i) Temperature (of the workpiece and the rolls), and (ii) the movement of rolls (rotation, speed, automatic gauge control, roll movement along the thickness direction of the workpiece, and automatic width monitoring) need to be controlled. In order to achieve this level of control, some aspects of known technologies have been used to develop some new rolling technologies.

In the following sections, some of these recently developed technologies are described. These include Heated Roll Rolling, Asymmetric Cryorolling, Variable-Gauge Rolling, and Through-width Vibration Rolling.

Heated-Roll Rolling

The Heated-Roll Rolling technologies are mainly applicable to light metals, especially for magnesium alloys.

Magnesium alloy strips make the lightest structural materials, which are widely used in the aerospace, automotive, and aviation industries, and in many other applications. Magnesium alloy strips are generally produced using the twin-roll casting and hot rolling techniques, but this entails the possibility of hazards such as explosions. During the hot rolling process, the microstructure of the strip material is affected by process parameters such as rolling velocities, rolling temperature, reduction ratio, etc. The deformability of magnesium alloy strips is poor during the cold forming process. This makes it very difficult to produce magnesium (alloy) by the cold forming method. These considerations suggest prompt a search for some better technique that might be used for magnesium products.

Kang et al [3] developed equipment that enabled uniform heating of the roll to produce magnesium strips. Li et al [4] developed a friction-and-wear tester in which the upper roll is heated, as shown in Fig. 2. The tester is used firstly to simulate roll wear during hot rolling. It is speculated that a similar technique can be used to produce magnesium strips.

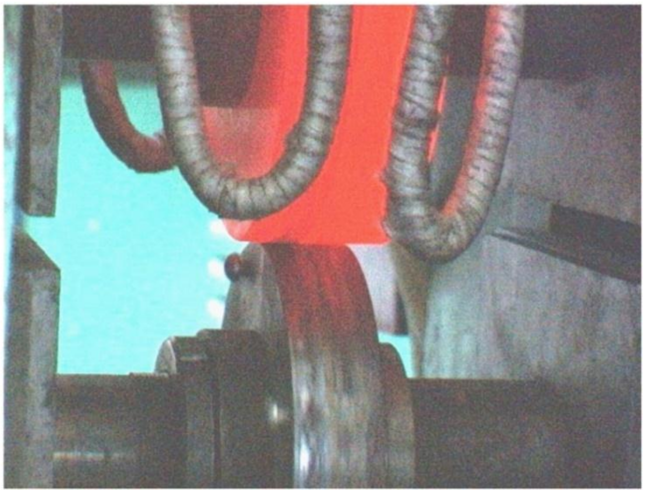


Fig.2 Upper disc and lower disc in a friction and wear tester

During the heated roll rolling process, the temperature rise of the workpiece is brought about by three ways: (a) thermal conduction from the roll to the strip; (b) heating associated with plastic deformation; (c) Frictional dissipation. To date, the contribution of each of the three mechanisms is yet to be quantified. To better understand these effects, we carried out computer simulations of the rolling process using the Finite Element (FE) method. The influences of roll temperature, reduction ratio, friction coefficient between roll and strip, initial thickness of strip on the temperature change in the strip were analyzed. In addition, an equation for prediction of the temperature of strip was established. Fig. 3 shows the simulated temperature change in strip during heated roll rolling [5].

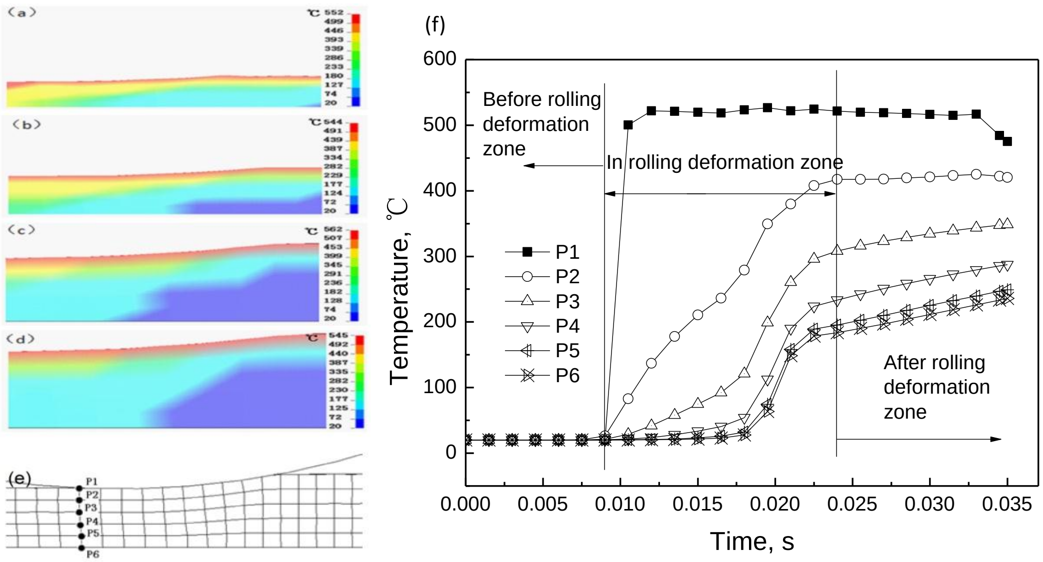


Fig. 3 Temperature change during heated roll rolling, (a) - (d) for variable initial strip thickness, (f) for the temperature change at points P1 - P6 in (e) in rolling deformation zone

Figure 3 shows a very significant rise in the strip temperature. This result is yet to be validated, but the simulations suggest that the technology is suitable for rolling cold magnesium strips. Through analysis of the temperature change in the strip as a function of roll temperature, reduction ratio, rolling speed, strip thickness, Equation (1) [5] is proposed to predict the mean temperature of strip at the exit of rolling deformation zone:

$$T_M = 46.8(1+0.00393T_R)(1+0.904\mathrm{e}^{-v_0/2.4118})(1+1.83\varepsilon+5.48\varepsilon^2)(1+2.27\mathrm{e}^{-h_0/0.9327}) \tag{1}$$

where T_M is the mean temperature of strip after rolling, T_R the roll temperature, v_0 the rolling speed, ε the rolling reduction ratio and h_0 the initial strip thickness.

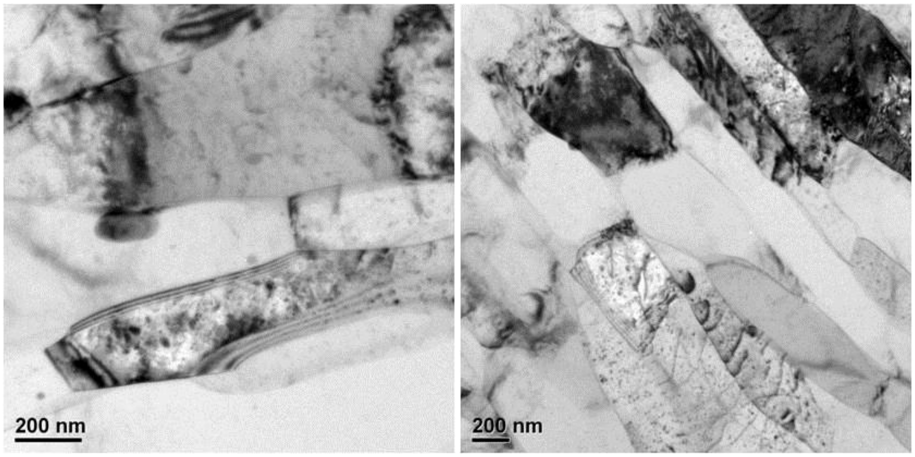
Asymmetric Cryorolling

In contrast to the above technique, in which the temperature of roll was changed, cryogenic rolling technology involves a change in the temperature of the workpiece.

In recent years, the production of materials with nano-sized grains by Severe Plastic Deformation (SPD) techniques has attracted much attention. This is due to improved physical and mechanical properties inherent to nano-structure materials. SPD techniques such as Accumulative Roll Bonding (ARB) [6], Dissimilar Channel Angular Pressing [7], High-Pressure Torsion [8], Equal-Channel Angular Pressing/Extrusion [9, 10], etc have been developed to fabricate bulk samples of nano-structure or ultrafine grain size from different metals. However, most of these techniques are only suitable for small samples, and only the ARB technique is appropriate for production of continuous nano-crystalline and ultrafine grain strips and plates.

The surface texture of the workpiece after each pass by the ARB needs to be monitored. It is also seen that edge cracks often appear in the product. Compared the above SPD technologies, the Asymmetric Cryorolling process has many of advantages. Cryorolling has potential for large-scale industrial applications of nanostructural materials. Due to the suppression of dynamic recovery during cryorolling, both the tensile strength and yield strength can be considerably increased, lowering the required plastic deformations.

We carried some experiments on the asymmetric cryorolling process for Al 1050 [11] and Al 6061 [12] alloys in a multifunction rolling mill. For Al 1050 , when the ratio of upper-to-lower rolling speeds is 1.4, the grain lattice dimension was seen to be 211 nm. This is much smaller than the 500 nm obtained by traditional asymmetric rolling, as shown in Fig. 4 [11]. Both the strength and ductility of Al 1050 increase with increase in the upper-to-lowerrolling speed ratio from 1.1 to 1.4. When this ratio is 1.4, the tensile stress reaches 196 MPa which is 22.3% greater than that with a rolling speed ratio of 1.1.



(a) (b)

Fig. 4 TEM of Al 1050 after rolling with ratio of upper to lower rolling speed (a) 1.1, (b) 1.4

Fig. 5 [12] shows the grain size of Al 6061 alloy resulting from a number of SPD processes. It is clearly that the asymmetric cryorolling has the ability to make the grain refinement compared to other SPD techniques.

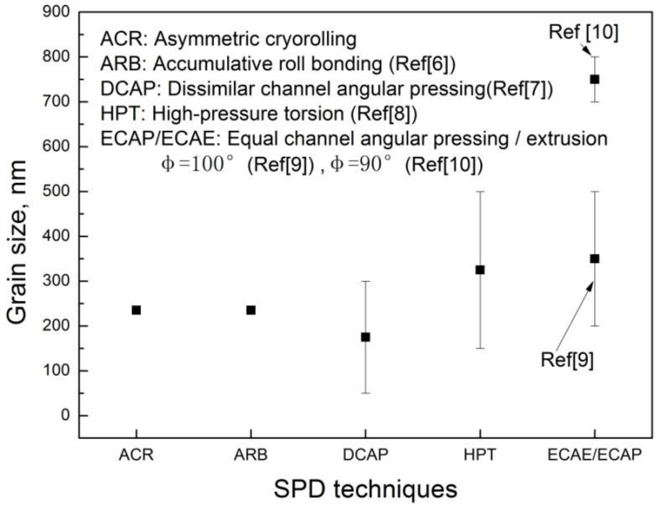


Fig.5 Grain size of Al 6061 alloy by different SPD techniques

The above two methods mainly involve the effects of the temperature of the roll/workpiece. The following methods focus on the movement of the rolls. When the rolling velocity of the upper and lower rolls is different, the result asymmetric rolling. On the other hand, when the movement of roll along the workpiece thickness is controlled, the result is variable-gauge rolling.

Variable-Gauge Rolling

In recent years, energy saving and emission reduction in the steel industry, particularly rolling with reducing resource consumption has attracted a great deal of attention. The Variable-Gauge Rolling process is a new technology to produce flat products with variable thickness (different thickness at different locations). Examples of such products include Longitudinal Profile (LP) plates, and Tailor-Rolled Blanks (TRB). LP plates are used in bridge building, architecture, shipbuilding, etc. TRBs are used in automobile manufacturing instead of Tailor Welded Blanks. Fig. 6 [13] shows a 170000 ton ship, which uses 2500 ton LP steel plates, with a shorter welding line of 700 m, thereby resulting in a 218 ton saving in the steel used. Variable-gauge rolled products have the following potential advantages [14]: (a) no sudden thickness change making special demand on mold due to welding seam, (b) greater safety, and (c) good energy absorption in the transition region; (d) lower maintenance costs, and (e) optimized matching of steel cross section to actual stresses. It would therefore be advantageous to examine this rolling technique in detail.

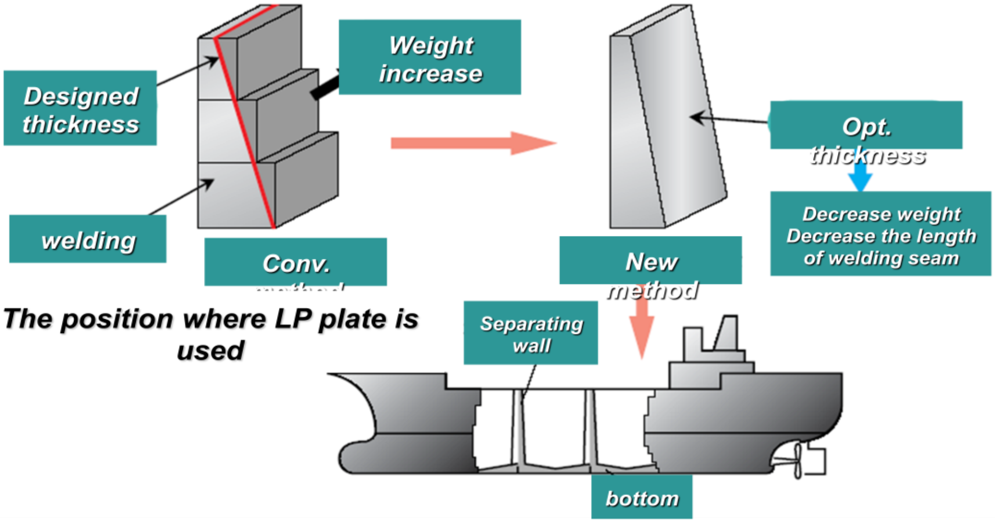


Fig. 6 170000 t ship, using LP steel plate 2500 t; shorter welding line 700 m, steel saving 218 t

Variable-Gauge Rolling can be applied in three ways [14]: (a) down-forward rolling, (b) flat rolling, and (c) up-forward rolling. The effects of these methods were studied by way of computer simulations of variable-gauge rolling under various reduction ratios. Fig. 7 [15] shows the variation in the rolling force for various reduction ratios. The rolling force is seen to increase by increasing the maximum reduction during rolling. Also seen are two transition zones with an abrupt change in the rolling force, accompanied by a vibration that is damped to different degrees. These are the zones when the rolling changes from down rolling to flat rolling, and when flat rolling changes to upper rolling. When the maximum reduction ratio is 40% (R_{max} = 0.4 in Figure 7), the change of rolling force in the transitional zones reaches 10000 kN, which is larger than 12.5% of the rolling force during flat rolling. When the maximum reduction ratio is 20% (R_{max} = 0.2 in Figure 7), the rolling forces change only slightly in the transitional zones.

This affects the strip thickness. In general, the vibration in the transition zones amounts to more than 10% of the stable rolling force, which will be a big problem for any automatic gauge control to deal with this abrupt rolling force wave. For that, it is very important to build a model to reduce the effect of the wave motion of rolling force on the quality of product. If the automatic gauge control system is adjusted using reduced thickness, roll flattening will decrease considerably, which will make the strip thinner in the transition zone. At the upper rolling stage when the thickness of the strip has been reduced, the rolling force also reduces sharply which will also result in thinner strip in the transition zone. Such effects are analyzed in Ref. [15], wherein we describe computer models developed to predict the rolling force wave in the process.

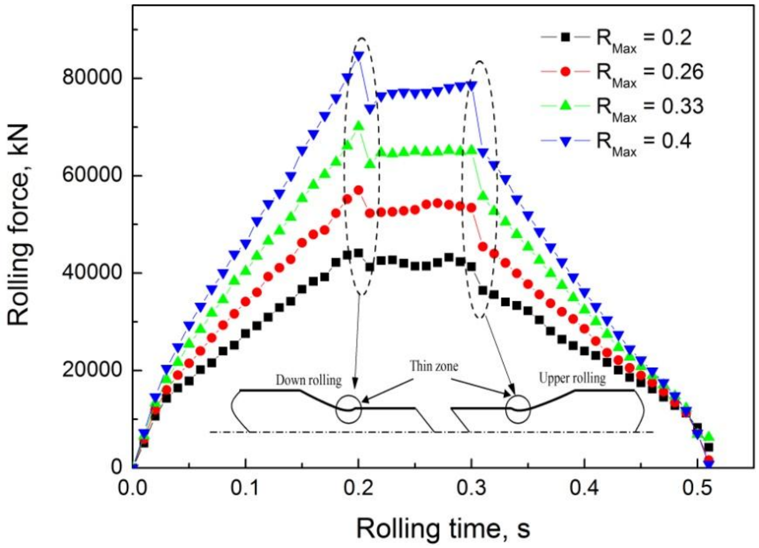


Fig.7 Rolling forces and their wave motion under various reduction ratios

Through-Width Vibration Rolling

The movement of the roll has three degrees of freedom. Movement of the roll along the strip width direction has been used in a conventional rolling process, such as the Sendizimir rolling mill. This is shown in Fig. 8 (a) [16], which is mainly used for strip profile control. However, the technique has been recently developed as the Through-Width Vibration Rolling technique by Chen et al [17], which is used to fabricate the ultrafine material sheets.

In the Through-Width Vibration Rolling technique [17], both rolls have rotational motion, powered by hydraulic motors. The bottom roll can have an additional synchronized vibration motion, applied by a hydraulic oscillator. In the resulting deformation, the workpiece is subjected to compressive stresses from the squeezing action of the rolls and shear stress from the friction between the rolls and the workpiece when the bottom roll vibrates along the direction perpendicular to rolling direction.

Chen et al [17] used the technique to continuously produce a high-strength aluminum sheet. Fig. 8 (b) [17] shows the yield strength and ultimate tensile strength of the TWVR sample as a function of the applied vibration amplitude for an Al-Mg-Si alloy. The yield strength of the TWVR sample is seen to increase from 380 MPa to 450 MPa as the amplitude is increased from 0 to 1.5 mm. The yield strength of the sample is seen to decrease from 450 MPa to around 420 MPa with further increase in the amplitude from 1.5 mm to 2.5 mm. It is obvious that the TWVR technique could improve the material property owing to the shear strain along the width direction resulting from friction between the roll and the workpiece.

Fig. 9 shows the results of computer simulations of this process in terms of the shear strain distribution in strips using the TWVR technique and conventional rolling technique. It is obvious that the former has larger shear strain, and the shear strain distribution is more uniform.

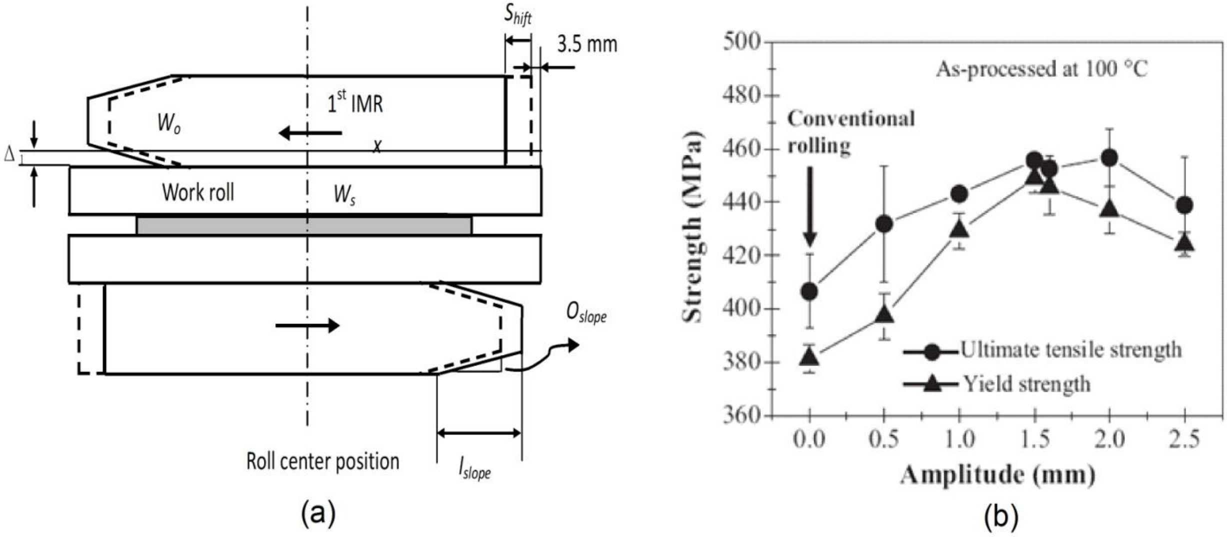


Fig. 8 Shift of roll in Sendzimir roll mill (a), and yield strength and ultimate tensile strength of the as-TWVR sample as a function of the applied amplitude (b)

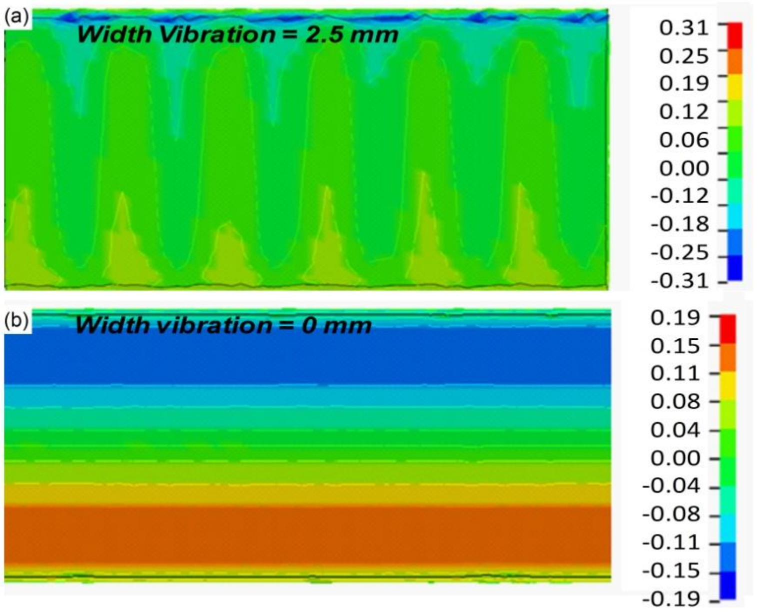


Fig.9 Shear strain distribution in workpiece (a) Through-Width Vibration Rolling, (b) Conventional rolling

Conclusions

This paper presents a review of a number of recent rolling technologies. These technologies can be broadly categorized according to the control of process temperature (heated roll rolling technology, cryogenic rolling technology involving severe reduction the rolling temperature) and movement of roll/workpiece (Variable-gauge rolling, and Through-Width Vibration Rolling). The Asymmetric Cryorolling method involves controlling both movement and process temperature. It is conceivable that a combination all of these techniques can result in more flexible and versatile rolling technologies in the future.

Acknowledgements

The lead author gratefully acknowledges the financial support from the Vice-Chancellor’s Fellowship Grant and URC small grant at the University of Wollongong, from the National Natural Science Foundation of China through Grant 51105071, and the Doctorate Foundation of the Ministry of Education of China through the Grant 20090042120005.

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