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Development and perspectives of rolling of rib stiffened plate

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Abstract. Thin-wide aluminium rib stiffened plate structure reduces the weight and provides high stiffness, which makes it in high demand in transportation vehicles, marine, and structural applications for energy saving and CO2 emission reduction. In this study, the applicability of rolling in manufacturing an integral rib stiffened plate is reviewed through analysis of different rolling processes. The effect of rolling parameters and rib geometry on the formation and quality of ribs are analysed. The analysis provides an important basis to advance the understanding of metal flow, viscoplastic deformation and roll shape design during rolling, significantly helping the design of an innovative rolling process for rib stiffened plate. In addition, geometry and rolling parameters, plate curvature, and roll pass design (RPD), that highly affect the rolling process design are discussed. This paper presents the limitations and improvements of specific shape rolling processes and preliminarily concludes that rolling could be a potential method to produce high quality thin-wide panels with high stiffeners.

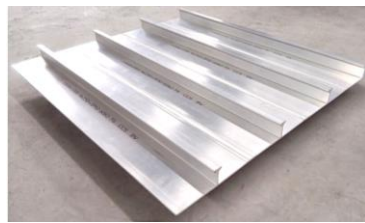
1. Introduction

Thin-wide aluminium stiffened plates are widely used in transportation, marine, and structural applications where light weight and high stiffness are essential. They provide stability and increase buckling resistance. This contributes to a reduction of fuel consumption, and thus contributes greatly to reduce carbon emissions. Common stiffener shapes are L (angle), T (tee), HP (bulb), and FB (flat bar), and a typical stiffened plate may consist of mainly 70% plates and 30% stiffeners at its cross-sectional area [1]. Figure 1 shows some examples of engineering structural applications of typical stiffened plates. Despite of advantages of carrying loads and reducing weight, fabricating these panels still faces many challenges.

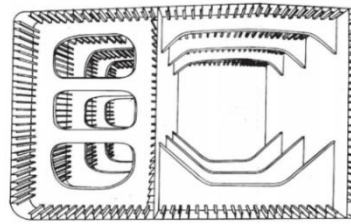
Stiffened panel fabrication processes are complicated and mainly include welding, riveting, or machining methods [2]. These conventional fabrications are not free from defects, such as less strength in the heat-affected zone (HAZ) due to welding [3], weight increase due to bolts in riveting [4], or much materials waste due to machining [5]. Therefore, developing a fabrication method to produce an integral thin-wide aluminium stiffened panel that avoids the above shortcomings has become highly demanded in industry.

The stiffened panel is also possible to be produced by extrusion processes but with a limited width, and further processes such as machining and rolling may be required [6]. By rolling process, it is possible to produce a plate with a width of 2000 mm, and a thickness of 1-3 mm with a single sequential rolling process [7]. However, it is much more challenging to roll a wide plate with multi-rib stiffeners. This paper reviews different rolling processes to develop an innovative rolling method to produce plate with multi-rib stiffeners.

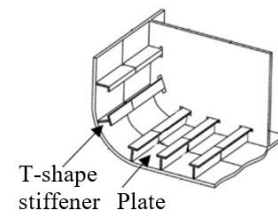




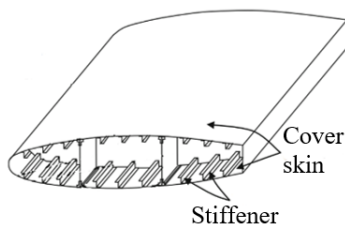
(a) Typical plate with stiffeners [8].



(b) Ship's hull girder [9].



(c) Stiffened panel [10].



(d) Aircraft wing structure [11].



(e) Storage constructure [12].



(f) Building roof structure [13].

Figure 1. Applications of ribbed panels for engineering structures.

2. Rolling methods

2.1. Flat and shape rolling

Understanding the concept of flat and shape rolling may significantly help to enable a method to roll a ribbed plate. These processes run into multiple passes with different roll profiles which are deformed plastically, and its shapes depend on the profile shape for each pass [14]. To roll section shapes successfully, the parameters of force, torque, spreading, extended length, and geometry should be properly specified [15]. The critical difference between flat and shape rolling is that in flat rolling there is less effort for designing shape roll pass because there are only two horizontal rollers used and it just needs to reduce the gap between them, and hence increase the reduction to the desired plate thickness. But in shape rolling, the geometry for each pass and deformation flow besides the previous factors in flat rolling are the key of designing shape rolled products. Therefore, rolling a ribbed plate is more complicated and difficult to predict and control the deformation and shape.

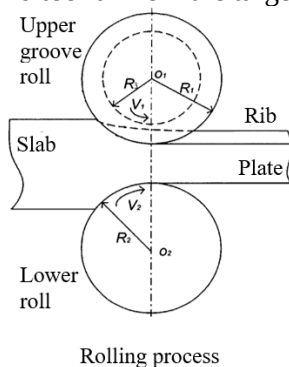
Much research has been carried out on flat and shape rolling. Panigrahi and Jayaganthan [16] studied the effect of rolling temperatures through different reductions on mechanical properties and microstructure of AA6063. It was found that strengths increased with increasing rolling reduction and decreasing rolling temperature while the ductile decreases. Devarajan et al. [17] investigated rolling parameters of cold strip rolling. Residual stress and rolling force decrease with increasing roll speed while they increase with increasing reduction, friction coefficient, and inlet thickness. Increasing roll diameter increases the roll force while it decreases the residual stress. Yershov et al. [18] reviewed and analysed rolling of a C-channel beam through different ways of rolling process designs. Rolling parallel and perpendicular flanges to the web is very difficult so flange slope is very important for successful rolling. The slop reduces the consumed power and increases the lifetime of rolls. Some of the C-section rolling methods fold the web to increase the angle of the flange to be easier for rolling.

2.2. Ribbed plate rolling

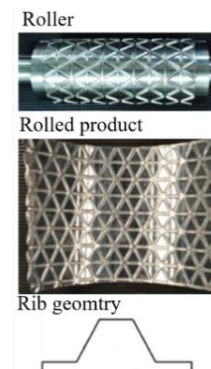
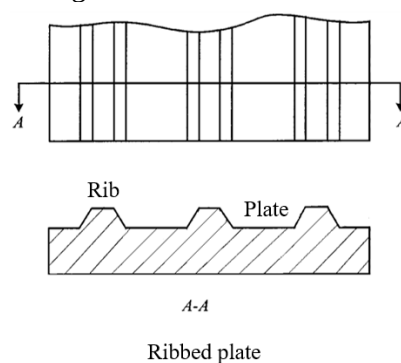
Although ribbed plate rolling has not been given as much attention as flat rolling, some researchers have addressed this topic. Studies on rolling of other shapes that have similar deformation behaviour and geometry help to understand how ribbed plate could be rolled. These can be generally divided into three groups: ribbed strip rolling, ring rolling, and shape rolling.

Figure 2 demonstrates some examples of rolling processes that can produce ribbed plate. Figure 2(a) shows a ribbed strip rolling process that consists of rolling mill (upper groove roll and lower flat roll), and a rolled product [19]. Jiang et al. [20] investigated ribbed strip rolling to analyse material flow, and

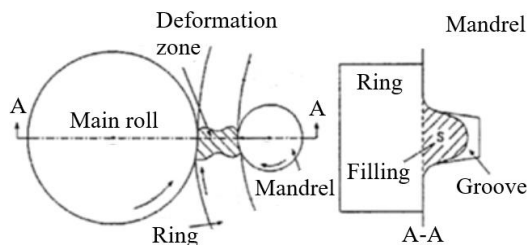
to study the influence of friction and reduction on the rib height. The same author also published a few papers about modelling of ribbed strip rolling and did some experimental verification [20-22]. The experiments were carried out to roll a carbon steel slab at 880-1000 °C and produced a ribbed strip with 6 mm strip thickness, 3 mm rib height, 8 mm rib thickness at the base of rib, and the rib profile was trapezoidal with 60° angle. Rib height increases with increasing reduction initially, then it starts to decrease with further increase of reduction (after 40% reduction). This phenomenon is known as pulling down due to inhomogeneous deformation, which may be reduced by increasing the inclined groove angle. It was also reported that rib height increases with increasing friction in the roll bite, and the rate of increasing the height at the entry zone is higher than that at the exit zone. Therefore, it is beneficial to enlarge the entry zone length and raise the friction especially at the exit zone to increase the rib height. However, the force required will be increased. Another interesting feature in this experiment is that the height distribution of the ribs along the width of the strip is varying. The middle ribs are higher than those on the sides because of the plate was experienced a spread on both sides during rolling which leads to decrease the rib height on both sides. The rib height (3 mm) was only 50% of the plate thickness (6 mm), and the rib inclined angle (60°) was too large when it is compared with a high vertical rib of a standard stiffened plate. For high thin rib, the process will be more complicated, and more roll passes are needed. Therefore, this process still needs further development to be capable of the projected design (high-thin ribbed plate). Zhi et al. [23] reviewed shaped flat rolling products technology including ribbed plate. It was classified that ribbed strip can be produced by groove rolling at high temperature. Schroller et al. [24] investigated the material flow for the production of ribbed plate by cold rolling for pure aluminium and concluded that the geometry of rib and sheet, and the friction coefficient have a significant influence on formed ribs and geometry shape. The rib was slightly formed in short height with less than 5% of sheet thickness (1 mm plate thickness, and 0.05 mm rib height) which is too short and too far from the targeted design.



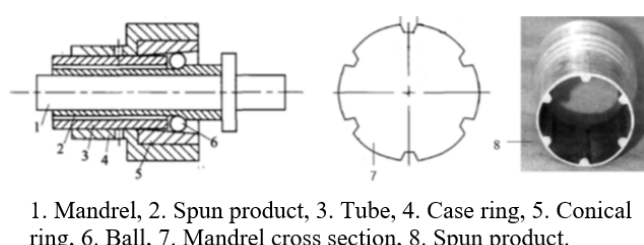
(a) Schematic of ribbed plate rolling process [19].



(b) Iso-grid strip rolling [25].



(c) Schematic of T-shape ring rolling [26].



(d) Spinning with inner longitudinal ribs [27].



(e) T-section rolling process by universal rolling mill [28].

Figure 2. Different rolling processes, and shape rolled products for ribbed plate.

Garrick et al. [25] developed a novel method of iso-grid strip rolling for AA1050, as shown in figure 2(b). It was concluded that rib direction significantly affects rolling forces and rib geometry shape. It was also concluded that inclined direction ribs (60°) are better than longitudinal direction ribs (0°) in geometry shape and filling the groove cavity. This is because, in longitudinal direction ribs, the deformation flows partially with rolling direction while in inclined direction ribs the roller squeezed the ribs to fulfill the grooves. In addition, the rolled plate experienced a camber due to asymmetric rolling which is expected. However, the rib geometry is still too thick compared to plate thickness and it has a large angle which is too far from the typical targeted design.

Figure 2(c) shows T-shape ring rolling process that applies between main roll and groove mandrel roll [26]. Zayadi et al. [29] investigated the filling groove profile for T-shaped ring rolling. It was concluded that filling the groove depth should be balanced with ring expansion. Therefore, rolling balance between rib and plate is significant and the final dimension should be considered. Li et al. [30] investigated the effect of roll sizes of T-shaped ring rolling for aluminium on the flow deformation, especially the effect of fillet radius of groove on the filling depth. It was reported that increasing fillet radius and driving roll diameter allow for more material to flow in which increase the filling depth. In contrast, increasing mandrel roll diameter decreases the filling depth. However, larger fillet radius and driving roll diameter with small mandrel roll diameter may cause cracking.

Figure 2(d) shows a balls spinning process which can be used to fabricate inner longitudinal ribs [27]. This process exerts a small deformation zone and relatively low applied loads. It produces a smooth surface, good tolerance, and a very thin wall. The produced spun dimensions were 2-3.5 mm in rib width, 2 mm in rib height, and 30 mm in diameter. It is noticed that the rib design has a slope to help in forming ribs, and the height of ribs are larger than the wall thickness, which is an advantage, but the rib geometry is roughly a square which is too far from the targeted design of high-thin rib.

T-section beam can be produced by different rolling methods such as groove rolling, however, in this method the web and flange has a taper which is considered a drawback [31]. It also can be produced by slitting H-section beam which has no tapers in both web and flange. Figure 2(e) shows a new method of producing T-section beam by tandem rolling with universal mills and edger [28]. This method was improved for better control of deformation flow and geometry between flange and web through edger roll as well as to produce a large slim T-section beam. This T-section beam was rolled by a universal mill, so this rolling process can be applied to produce a one rib stiffener with plate, but it is impractical for multi-stiffeners. Therefore, using groove rolling to produce multi-ribs stiffened plate maybe most applicable among rolling processes. However, preparation of pre-forms of the plate before groove rolling could be necessary because of the geometry design of ribs are high and thin.

2.3. Use of pre-form shape

Rolling a pre-formed shape could be a good idea to produce rib stiffeners with plate. Design an optimum slab geometry shape before rolling may improve the final rolled product in many aspects, i.e., quality, tolerance, and economics. Qian et al. [32] optimised four blank designs of T-section shape ring rolling. One was a rectangular cross-section, and the others were pre-formed with a T-shape cross-sections with various flange heights. After ring rolling processes, three blanks experienced volume deformation flow from the outer ringside (web) to the inner ringside (flange), which is considered a disadvantage known as inhomogeneous deformation. This flow leads to accumulating the material at the surface and struggling to create a flange. The optimum design experienced less inhomogeneous volume flow deformation. The reason behind this was the volume of web and flange for both initial blank and final product were at the same cross-section area ratio which means there was a good balance between web and flange during rolling. Another advantage for the best pre-formed blank is that it exhibited less plastic strain (around 25% of what rectangular cross-section blank required) during rolling which required less force and power to form. Qi and Li [33] reviewed the design of blank geometry shape in ring rolling and reported that the blank geometry shape plays a significant role in forming the final shape of ring rolling products. It also reported that inappropriate blank geometry may lead to under-filling or over-filling the groove, and some defects. The equality of volumes and similarity of shapes before and after rolling improve the optimum design. Therefore, pre-forming a slab with rib stiffeners before rolling is a good idea and maybe capable of rolling a high-thin ribbed plate successfully. Applying groove rolling

on a pre-form plate allows to apply a reduction rolling on the ribs instead of filling the high-thin grooves by material through rolling which is much more difficult. Also, it is important to balance the geometry design during rolling for both rib and plate cross-section areas to achieve a homogenous flow deformation as much as possible. Using the same reduction rolling for both rib and plate will produce almost the same extended lengths for both which leads to avoiding the curvature.

2.4. Curving

Curving is highly expected during rolling of a ribbed plate. This is because of using different groove roll diameters for rib and plate which leads to bending the ribbed plate. Figure 3 presents schematically an example of bending of asymmetric rolling for a typical ribbed plate, indicating the curving direction. Philipp et al. [34] analysed the front-end bending of flat plates influenced by speed and geometry. They pointed out that the bending depends on the shape factor (the ratio of projected contact length to the mean thickness), and the circumferential speed of rolls. Applying a small reduction and with a small shape factor, the plate bent toward work roll with less circumferential velocity. Then it bent toward the work roll with higher circumferential velocity after increasing the reduction and shape factor. In general, larger differential velocities between rollers increased the curvature. Similar conclusions have also been reached by Kasai et al. [35]. In addition, thicker plate experienced less curvature than thin plates. The study was on a general curvature behaviour associated with a flat plate, but it will be more complicated and difficult to control with a ribbed plate. As mentioned earlier, Takashima and Hiruta [31] introduced a new method of rolling a high-thin T-section beam by a universal rolling mill and found that the curvature can be controlled by the thickness reduction balance between web and flange. Similar thickness reduction applied on both web and flange may lead to produce a straight T-bar. In contrast, the T-bar will be bent toward the less thickness reduction of either web or flange. However, if the thickness reduction of flange exceeds the web thickness reduction by a few percent, the T-bar may not bend. Wave edge defect may appear during rolling high-thin web if the web reduction is larger than flange reduction resulting in curving the bar toward the flange. Then during straightening the bar, the web experiences compressive stress. Also, edge wave may show when applying large thickness reductions for both web and flange.

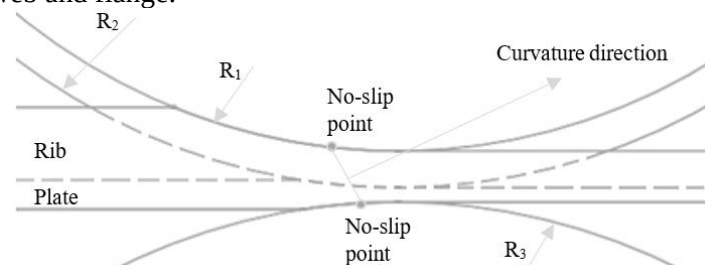


Figure 3. Example set-ups and bending of asymmetric rolling for typical ribbed plate.

2.5. Roll pass design (RPD)

The benefit of good roll pass design (RPD) is to produce correct geometry profile shape with good surface and properties, and to minimise the final cost in term of reducing the required energy, reducing number of passes, operation time, and labour as well as extending the service life of rolls and tools [36]. There is increasing availability of RPD data that can be studied and analysed to produce a general approximated design method for new geometry products such as a ribbed plate. Ribbed plate design will communicate beams and sheets that have similar deformation flow behaviour. To develop a RPD for aluminium ribbed plate, it may be better to roll a pre-formed shape to achieve the final desired profile. This is because it is difficult to start with bloom to split and breakdown it in the same way as in steel beam rolling. Aluminium has lower formability and higher expansion than steel which make it difficult to roll a complicated shape with multi-high-thin rib stiffeners with a wide plate [37]. Some principles should be followed during design such as, distributing the press force of the rolls between rib and plate, avoiding sharp angles by adding fillet radius, and adding a slope for the rib.

3. Discussions

It is a challenge to produce high-thin rib stiffeners with a wide plate by the rolling process. This is because high-thin ribs are difficult to create, and it will struggle to fill the narrow groove cavity. As shown earlier, some researchers produced rib stiffeners with plate but with relatively short-thick rib and inclined rib surface. Therefore, rib geometry (height, width, and inclined surface) plays a significant role in producing ribbed plate by rolling. Other researchers use pre-formed shapes to help in creating ribs and keep the deformation flow homogeneous. This can be applied by keeping the volume of rib and plate before and after rolling in the same range as much as possible, which means using the same reduction of rolling for both. Producing stiffened plates using T-section by universal rolling mill is suitable for single ribbed plate but may not be applicable for multiple ribs. Groove rolling is another applicable rolling process for ribbed plate. However, the rolled product may experience difficult entry of ribs through groove slots because they are very thin slots. Therefore, any defects show on ribs such as front-end bending will increase the difficulty of rolling entry of the ribbed plate especially for multiple passes process because it will increase sequentially per pass. In addition, the alignment between groove slots and ribs is of concern.

Shape factor (ratio of projected contact length to mean thickness) and circumferential speed of rollers directly influence the bending of the ribbed plate. There can be two different shape factors and two to three different circumferential roller speeds in the same rolling process for ribbed plate. Shape factors and speeds should be controlled and balanced to apply the same reductions and produce the same extended lengths to avoid bending. However, in using groove rolling, shape factor, roll speed as well as a pre-form slab and ribbed product must be designed carefully. This is because groove rolling is not flexible to control the rolling parameters. Also, rolling process parameters significantly affect the rib forming, such as friction and reduction. Increasing these parameters will increase the rib height and the filling forming. These parameters should be designed carefully to create good tolerance and quality product.

4. Conclusions

This paper has reviewed different rolling processes for producing ribbed plates. Rolling a rib stiffened plate, especially for multiple ribs, is still a challenge and needs more attention in future. The following conclusions can be drawn:

- Rolling is a potential method to produce high quality thin-wide panels with high stiffeners. Groove rolling is one of the most suitable rolling processes to produce multi rib stiffeners with wide plate. Using pre-forms for rolling is advantageous in manufacturing better quality ribbed plates.
- Rib geometry (height, width, inclined surface) is the key of producing ribbed plate by rolling. A higher and thinner groove increases the difficulty of rib forming. On the other hand, radius fillet and inclined surface of groove help to create ribs during rolling.
- Reduction balance between plate and rib during rolling can produce the same extended lengths for both and help to avoid bending. Optimum shape factors and proper differential circumferential speeds lead to producing straight ribbed plate.
- Friction and reduction have significant effect on creating high rib. Increasing these parameters increase the rib height.

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