Analysis of strip shape and profile, and mechanical properties during asymmetrical cold rolling

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ABSTRACT: *Optimization of rolling parameters to achieve better strip shape and to reduce rolling force is a challenge in rolling practice. In this paper, thin strip rolling process of low carbon steel has been investigated under asymmetric rolling conditions at various combinations of rolling parameters under lubrication. The effects of strip width, reduction ratio and rolling speed on strip shape with consideration of speed ratios, work rolls cross (WRC) angles and work shifting (WRS) values are discussed. Results show that increasing work rolls cross angle results in a better strip shape and reduction of rolling force, as well as the effect of work roll shifting value on strip shape. The strip crown and edge drop improved with increasing work roll cross angle. The improvement is more significant when the speed ratio is increased. The strip hardness reduced with increasing work roll cross angle and more pronounced at higher speed ratio. However, there was no noticeable change in microstructure in any case.*

Keywords: *Cross shear reign, speed ratio, strip shape and profile, work roll cross angle, work roll shifting value.*

I. INTRODUCTION

The electronics and instrument industries widely employ cold rolled thin metallic strips [1, 2] as they require exceptional accuracy, precise profile and flatness of the strip. The demand for high quality and productivity of thin strip has compelled industry to operate at higher performance standards to remain competitive [3] worldwide and producing thinner strip is significant consumptions of cost and time for industries [4, 5]. On the other hand, because of the elastic deformation of the rolls during rolling process, maintaining thin strip shape and profile and dimensional accuracy are a difficult task [2]. The shape and profile of the thin strip have a great influence on both the rolling process and quality of the product [6]. The quality of strip is mainly governed by the optimisation of the rolling parameters, such as the rolling speed, reduction, strip width, friction, rolls pair cross angle and work roll shifting value. Thus, if the rolling parameters are imperfectly specified, the loading force causes elastic deflections of rolls [7, 8], which result in the effect on the shape and profile of the rolled strip and thus its quality. Continuous variable crown (CVC) and pair cross (PC) mills are designed to control the strip shape, profile and flatness when the rolling process is applied to the rolling of thick strip, and the control of the strip shape, profile and flatness for relatively thick products [9]. However, for thinner gage strip (< 0.2 mm) the strip shape control is still a challenge in rolling practice.

Friction is of paramount importance in the rolling process, an excessive friction may impede the plastic flow of material [10]. Rolling force, rolling speed, pressure distribution, reduction, surface quality, strip shape and profile are all influenced by magnitude of friction and the applied lubricant[2, 10-13]. However, there is no evidence on the effect of work roll cross angle and shifting on friction coefficient.

Work roll crossing involves increasing the roll gap with increasing distance from the roll centre [14] by slightly crossing the rolls and reducing the roll force across the roll from the centre to the edge of the strip, as shown in **Fig.1a**. The most efficient roll cross system is the work roll cross system, while the least efficient one is backup roll cross systems [15].

Work roll shifting improves the strip thickness and flatness by shifting rolls with special shapes. Work roll shifting mill is the most effective one for strip shape control [15, 16]. It improves the accuracy of strip crown and edge drop, as well as, permits schedule free rolling [17, 18] by changing the gap equivalent profile in the roll bite [19, 20] as shown in**Fig.1b**.

Axial side shifting of work rolls using cyclic shift method has shown to evenly distribute the roll wear until a smooth roll crown can be obtained [21].

Another technique to improve the strip profile and reduce the rolling force is asymmetric rolling which is characterized by a geometric asymmetry linked to the difference of diameters between the two rolls. In asymmetric rolling, the cross shear region is generated between the backward and forward slip zones [10]. There have been several studies to demonstrate that the cross shear region reduces the rolling force up to 40% , as well as considerable reduction in strip thickness compared to conventional rolling [22, 23]. Reduction of rolling force has a major advantage that very large strains can be imparted into the material for producing ultra-fine grain structures, modification of textures and production of high strength materials.

Work roll cross angle and shifting have shown to improve the strip shape and profile. However, there is no evidence in the literature to demonstrate if the strip shape and profile can further be improved by using work roll cross angle and work roll shifting under asymmetric rolling performed at a certain speed ratio. To the best of author's knowledge, no such studies have been conducted. Therefore, the current study is novel in its framework and will contribute to field of knowledge by filling this gap.

In this study, asymmetric cold rolling of thin low carbon strip under lubricated condition will be investigated at speed ratios of 1.1 and 1.3. The effect of various parameters such as work rolls cross angle, work roll shifting values, strip width, rolling speed and reductionon the strip shape, profile and rolling force will be investigated.

II. EXPERIMENTAL METHOD

A 4-high Hille 100 rolling mill was employed to carry out the cold rolling of 0.5mm x 400mm low carbon steel strip at 80.0 and 100.0mm widths. The rolling mill parameters are listed in **Table 1**. Rolling force was measured through a load cell mounted on the backup roll, whereas, the torque was measured by a sensor cell connected to the gearbox and backup roll. The roll nick was adjusted to obtain the various cross angles and roll shifting was obtained by using screw shafts in the upper and lower slide blocks to axially slide the upper work roll towards the operator side and lower slide block towards the drive side. This is schematically shown in **Fig.2**. Cold rolling was performed using Hyspin AWS100 lubricantat speed ratios of 1.1 and 1.3, roll speeds of 20.0rpm (0.0659 m/s) and 30.0rpm (0.0986 m/s), rollscross angle of 0^o, 0.5^o and 1.0^o and roll shifting of 0, 4.0 and 8.0mm.Strip hardness was measured using Struers DuraScan-70 hardness tester and microstructure was studied under a Color 3D Laser Microscope (VK-X100/X200 Series – VK Viewer). The resulting microstructure has been measured by Scanning Electron Microscopy (SEM).

Table 1 – Rolling Mill Parameters

Mill system	**Work roll crossing and shifting**
Upper work roll	63.0mm diameter, 250.0mm long
Lower work roll	69.0 and 82.0mm diameter, 250.0mm long
Backup roll	228.0mm diameter, 250.0mm long
Rolling force	0-1500.0kN
Rolling torque	0-13.0kNm

III. RESULTS AND DISCUSSION

3.1. Effect of work rolls cross angle

The effect of work roll cross angle on the thickness profile of exit strip under lubrication at 1.1 speed ratio is shown in **Fig.3a**. At 0^orolls cross angle, the thickness decreased significantly towards the strip edge resulting in an increase of the strip crown. The great variation of thickness near the strip edges is attributed to the fact that the resistance of transverse flow in the area near the strip edges is relatively low and this reflects the character of the general strip profile produced with conventional rolling mill. The strip thickness decreased with increasing rolls cross angle from 0^o to 1^o. There is also a significant improvement in strip profile indicating that the work roll crossing system has an ability to adapt the roll gap profile causing the roll gap distribution to be uniform. This leads to obtain large efficiency of shape and profile control.At a speed ratio of 1.3 (**Fig.3b**), there is relatively better outcome such that there is a significant improvement in strip thickness as well as strip profile with increasingwork rolls cross angle. This indicates that a higher speed ratio makes better roll gap distribution, which is primarily controlled by changing the rolls cross angle.

In order to illustrate it more clearly, the metric of crown and edge drop are used to estimate the strip profile.The strip crown C_5 is defined as the variation value between the thickness at the strip center and thickness at a 5.0mm distance from the edge, and the ege drop C_e is defined as the variation value between the thichness at the 35.0mm distance from edge and the thickness at 10.0mm distance from the strip edge. At 1.1 speed ratio, the strip crown and edge drop decreased with increasing rolls cross angle (**Fig.4a**). However, the reduction in the strip crown and edge drop is more pronounced at the higher speed ratio of 1.3 (**Fig.4b**), which is as expected due to better roll gap distribution at higher speed ratio.

A mean grain size of ~20.0μm is observed at 1.1 speed ratio with no appreciable change in grain size or grain refinement that can be associated with increasing work roll cross angle as shown in **Fig.5a**. Increasing speed ratio to 1.3 also did not result in any significant changes in the microstructure with increasing work roll cross angle as shown in **Fig.5b**.

3.2. Effect of work rolls shifting value

The effect of work roll shifting value on strip profile and thickness at speed ratio 1.1 is shown in **Fig.6a**. Rolling was carried with no work roll cross angle to investigate only the effect of work roll shifting. There is only a slight improvement in strip profile and thickness with increasing work roll shifting value. Due to relative shifting between the upper and lower rolls, there is a uniform distribution of rolling pressure, essentially decreasing the force required to achieve the desired thickness. However, increasing speed ratio to 1.3 improved the strip profile and thickness. This is due to the greater cross shear region between the backward-slip zone and the forward-slip zone which reduces the required rolling force and results in a greater reduction in thickness(**Fig.6b**).

At higher speed ratio, the uniformity of rolling pressure is maintained, resulting in an improved strip profile. However, increasing work roll shifting value did not improve the microstructure regardless of the speed ratio as shown in **Fig. 7a** and **b**.

3.3. Effect of work roll cross angle and work roll shifting value on rolling force

At 1.1 speed ratio, the rolling force decreased by about 10.0kN with increasing rolls cross angle (**Fig. 8a**). This may be as a result of decreasing the contact area between the work roll and the backup roll, which ultimately reduces the rolling pressure, therefore providing a low resistance to the transverse flow of metal. At higher speed ratio of 1.3, the rolling force significantly dropped by about 20.0kN (**Fig. 8a**). Since higher speed ratio requires a larger difference in diameters of the top and bottom work rolls, this effectively reduces the contact area between the work roll and backup roll. Therefore, the rolling pressure is reduced significantly resulting in lower rolling force.

With increasing work roll shifting value, there is only a slight reduction in rolling force (about 5kN) at 1.1 speed ratio (**Fig.8b**). However, increasing speed ratio to 1.3 resulted in about 20.0kN reduction in rolling force with increasing work roll shifting value. As indicated above, the higher speed ratio provides uniformity of rolling pressure with increasing work roll shifting value, therefore, reducing the required rolling force.

Results also indicate that increasing work roll cross angle improves the strip profile, reduces the strip thickness, strip crown, edge drop and rolling force under asymmetric rolling conditions. The change in speed ratio from 1.1 to 1.3 produced a better strip profile, reduced strip thickness, strip crown and rolling force. Increasing work roll shifting value improves the strip profile but only slightly. However, increasing the speed ratio shows significant improvement in strip profile and corresponding reduction in pressure on the work rolls, therefore, reduced rolling force. However, there is no associated change in microstructure.

3.4. Combined effect of work roll cross angle and work roll shifting value

The combined effect of work roll cross angle and work roll shifting value on profile and thickness of the exit strip at speed ratio 1.1 is shown in **Fig.9a**. At maximum work roll cross angle andwork roll shifting value, the strip profile is improved. However, with the same rolling parameters at 1.3 speed ratio, the strip profile is almost horizontal (**Fig.9b**). This indicates that a super strip profile can be obtained with maximum work roll cross angle and maximum work roll shifting at higher speed ratios.

3.5. Effect of strip width

The strip profile at speed ratio 1.1 and 80.0mm and 100.0mm widths is shown in **Fig.10a** and **b** respectively. The strip profile improved and strip thickness reduced with increasing work roll cross angle regardless of the strip width.Upon increasing the speed ratio to 1.3, the strip profile and strip thickness both improved with increasing work roll cross angle (**Fig.10c** and **d**).An almost identical strip profile is obtained at both speed ratios, however, the strip thicknesswas found to reduce more at higher speed ratio of 1.3.This is attributed to a large cross shear region between the backkward-slip zone and the forward-slip zone at higher speed ratio which reduces the required rolling force and results in a greater reduction in thickness.

At 1.1 speed ratio, the rolling force tends to reduce with increasing work roll cross angle, however, an increase in width from 80.0mm to 100.0mm increased the required rolling force by about 20kN (**Fig.11a**). Increasing the speed ratio to 1.3 tends to have a more prominent effect on rolling force with increasing work roll cross angle (**Fig.11b**). The difference in rolling force with strip width is approximately same at both speed ratios. As the strip width increases, the net contact area becomes larger, which increases the rolling pressure on the work rolls, therefore, requires more rolling force. It is noted that the strip experienced a higher rolling force at a speed ratio of 1.1 than that of 1.3, irrespective of the strip width and work roll cross angle.This is due to the greater cross shear region between the backkward-slip zone and the forward-slip zone which reduces the required rolling force.

3.6. Effect of rolling speed

As seen in **Fig.12a**, for the speed ratio of 1.1, there is no significant improvement in the strip profile with increasing cross angle at a rolling speed of 20.0rpm. At 30.0rpm also, there is no significant improvement in strip profile, however, there is a significant reduction in strip thickness (**Fig.12b**). For the speed ratio of 1.3, the strip profile and thickness are improved at both 20.0 and 30.0rpm, however,it is significant at 30.0rpm. This is because of the combined effect of higher rolling speed which reduces the friction between the rolls and a greater cross shear region between the backward and forward slip zones due to higher speed ratio. These two factors significantly improve the strip profile and reduce the strip thickness (**Fig.12c** and **d**). The strip experienced a higher rolling force at 1.1 speed ratio with slight reduction with increasing work roll cross angle, regardless of rolling speed. (**Fig.13a**). By increasing the speed ratio to 1.3, the rolling force was found to be much less and dropped significantly with increasing work roll cross angle (**Fig.13b**).Higher work roll cross angle provides a uniform roll gap distribution over the contact area, thus reducing the rolling pressure. This effect is more pronounced when there is a significant difference between the upper and lower work roll diameters resulting in a higher speed ratio, therefore, reducing the required rolling force.

3.7. Effect of reduction

At the speed ratio of 1.1, an identical strip profile is obtained at 20.0% and 30.0% reduction ratio with increasing work roll cross angle (**Fig.14a** and **b**) respectively. However, 30.0% reduction ratio results in higher thickness reduction with increasing work roll cross angle for the same set of rolling parameters. When the speed ratio is increased to 1.3, the strip profile is almost flat regardless of the reduction ratio, however, a larger reduction in thickness at higher reduction ratio (**Fig.14c** and **d**).Due to the large difference between the work roll diameters at the higher speed ratio, there is a larger roll gap distribution which further enhances the uniformity of roll gap distribution with increasing work roll cross angle. Therefore, the strip profile tends to be flatter. However, a higher reduction ratio does not change the physical parameters of the process.

3.8. Effect of work roll cross and work roll shifting on strip hardness

At the speed ratio of 1.1, the strip hardness was found to be higher for 30.0% reduction ratio than 20.0% reduction (**Fig.15a** and **b**). This is because a higher reduction requires higher pressure on the work rolls, which essentially increases the plastic deformation of the metal during rolling process. With the increase in plastic deformation of the material, the dislocation density increases, resulting in higher hardness. The hardness decreased with increasing work roll cross angle at both reductions, which is essentially due to the fact that higher work roll cross angle provides more uniform roll gap distribution, therefore, reducing the rolling pressure, thus a less resistance to metal flow even at the higher speed ratio of 1.3, the strip hardness was found to be higher for 30.0% reduction and in both cases, decreased with increasing work roll cross angle (**Fig.15c** and **d**).For the same set of rolling parameters, the hardness was also found to reduce with increasing speed ratio. Moreover, with increasing work roll cross angle, the reduction in hardness is more pronounced at higher speed ratio. This is because of the reduced friction between the work rolls which results in lower rolling force. Therefore, there is less plastic deformation at higher speed ratio, hence a reduced hardness.

As for the 2nd pass, the exit strip profile at a speed ratio of 1.1 improved with increasing work roll cross angle and a slight decrease in thickness (**Fig.16a**). When the speed ratio is increased to 1.3, the strip profile is almost flat with significant reduction in thickness (**Fig.16b**).The main purpose of increasing work roll cross angle is to provide uniform roll gap distribution, therefore, less resistance to metal flow, thus, improved strip profile. When the speed ratio is increased, it further improves the roll gap distribution due to difference in top and bottom roll diameters, therefore, further improving the strip profile and reducing the strip thickness.
The rolling force at 1.1 speed ratio was found to be higher than at 1.3 speed ratio (**Fig. 17a** and **b**). This is because at higher speed ratio, the cross shear region between the backward and forward slip zones results in a significant decrease in required rolling force and also significantly reduces the strip thickness. The rolling force was found to be reduced with increasing work roll cross angle and work roll shifting value at both speed ratios.
The exit strip profile and strip thickness at the 2nd pass at a speed ratio of 1.1 and 1.3 are improved with increasing work roll shifting value but not as significant as thatin work roll cross angle (**Fig. 18a**and**b**) respectively. Work roll shifting only provides uniform distribution of rolling pressure which decreases the required rolling force and thus has little effect on strip profile.

For the 3rd pass, the exit strip profile at the 3rd pass at a speed ratio of 1.1 was improved with increasing work roll cross angle and with a slight decrease in thickness (**Fig.16a**).However, when the speed ratio increased to 1.3, the strip profile is almost flat with significant reduction in thickness (**Fig.16b**). This is because as the work roll cross angle increases, the roll gap distribution become uniform, thus, less resistance to metal flow, as a result, improved the strip profile. When the speed ratio is increased, it further improves the roll gap distribution due to difference in top and bottom roll diameters, therefore, further improving the strip profile and reducing the strip thickness.

The exit strip profile and strip thickness distribution at the 3rd pass at a speed ratio of 1.1 and 1.3 were improved with increasing work roll shifting value but not as significant as that with the work roll cross angle (**Fig.18a** and **b**).

At speed ratio 1.1, a rolling force of ~163.0kN is required under no work roll cross angle and no work roll shifting conditions. The rolling force decreased by about 16.0kN with increasing work roll cross angle and no work roll shifting. However, it dropped only by 8.0kN with increasing work roll shifting value and no work roll cross angle (**Fig.19a**). Atthe speed ratio 1.3, the required rolling force under no work roll cross angles and no work roll shifting is ~148.0kN compared to 163.0kN at 1.1 speed ratio. This significant reduction in rolling force is due to the asymmetric rolling which produces a significant cross shear region between the backward and forward slip zones which results in a significant reduction in rolling force. The rolling force further decreased by about 8.0kN with increasing work roll cross angle and no work roll shifting. But it dropped only by 2.0kN with increasing work roll shifting value and no work rollcross angle (**Fig.19b**). Increasing work roll shifting value does not help maintain a uniform roll pressure; therefore, there is no significant drop in rolling force as expected.

For a 30.0% reduction under maximum work roll cross angle and no work roll shifting value at the highest speed ratio of 1.3, the maximum strip thicknesses were found to be 0.35.0mm (1st pass), 0.24.0mm (2nd pass) and 0.18.0mm (3rd pass). This indicates that under the same conditions of rolling, the 2nd pass resulted in a thickness reduction of ~0.1mm whereas the 3rd pass results only ~0.7.0mm. The plastic deformation caused during rolling increases the strength of the material due to increased dislocation density. With successive passes, the material gets stronger, and therefore, under the same rolling conditions, the reduction in strip thickness gets smaller at each pass.

IV. CONCLUSIONS

Cold rolling of low carbon steel was carried out under lubrication at speed ratios of 1.1 and 1.3 to investigate the effect of rolling parameters such as work roll cross angle, work roll shifting value, rolling speed, strip width and reduction ratio under asymmetric rolling conditions. Following are the conclusions of this study:

- Increasing work roll cross angle and work roll shifting improve the strip profile, strip crown and edge with corresponding reduction in strip thickness. However, the effect is more significant with work roll cross angle. There is also a significant reduction in rolling force. A combination of maximum work cross angle and shifting value further improves the strip profile and thickness. However, at higher speed ratio under the same conditions of rolling, the strip profile is almost horizontal. A higher speed ratio increases the cross shear region between forward and backward slip zones which results in significant drop in rolling force.
- An increase in width from 80.0mm to 100.0mm increased the required rolling force. The difference in rolling force with strip width is approximately the same at both speed ratios. As the strip width increases, the net contact area becomes larger, which increases the rolling pressure on the work rolls, therefore, requires more rolling force. The strip experiences a higher rolling force at lower speed ratio irrespective of the strip width and work roll cross angle.
- A combination of higher rolling speed and higher speed ratio results in a significant improvement in strip profile. This is because of the combined effect of higher rolling speed which reduces the friction between the rolls and a greater cross shear region between the backward and forward slip zones due to higher speed ratio.
- A flat strip profile is produced at a higher speed ratio regardless of reduction ratio, however, a larger reduction in thickness is achieved at higher reduction ratio.
- The hardness decreased with increasing work roll cross angle irrespective of reduction ratio because of more uniform roll gap distribution, therefore, reducing the rolling pressure, thus a less resistance to metal flow. Even at the higher speed ratio of 1.3, the strip hardness was found to be higher and decreased with increasing work roll cross angle.
- There was no noticeable change in microstructure with increasing work roll cross angle.

- A higher speed ratio in combination with optimum rolling parameters such as high work roll cross angle, high work roll shifting results in a highly improved strip profile, reduced thickness and a low rolling force.

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VI. Tables caption

Table 1 – Rolling Mill Parameters

VII. Figures caption

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Fig. 7 Cross section microstructure of rolled strip for (a)speed ratio 1.1, and (b) speed ratio 1.3, 80.0mm width, 30.0rpm, 20.0% reduction and no work roll cross angle and work roll cross angles: (a) 0 , (b) 4.0mm and (c) 8.0mm – Lubricated- 1^{st} Pass

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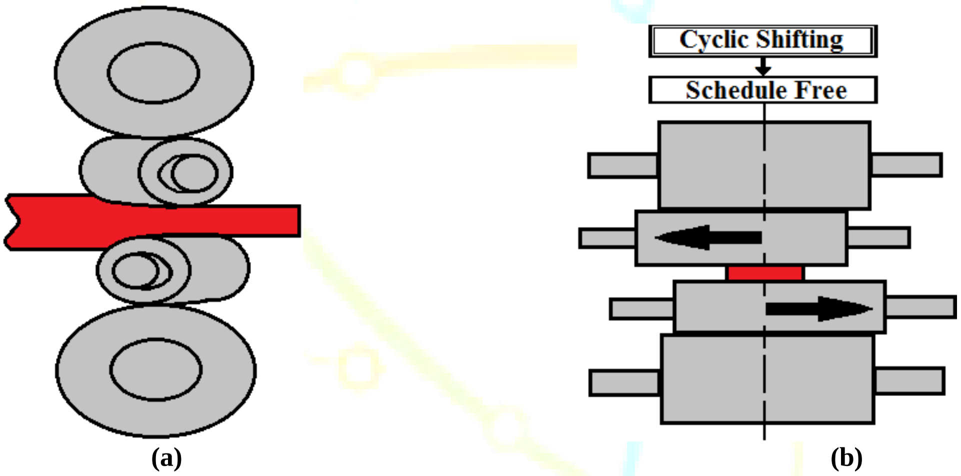


Fig. 1 (a), Effect of work rolls cross angle on roll crown [20], and (b) Cyclic Shifting Method (CS) [21].

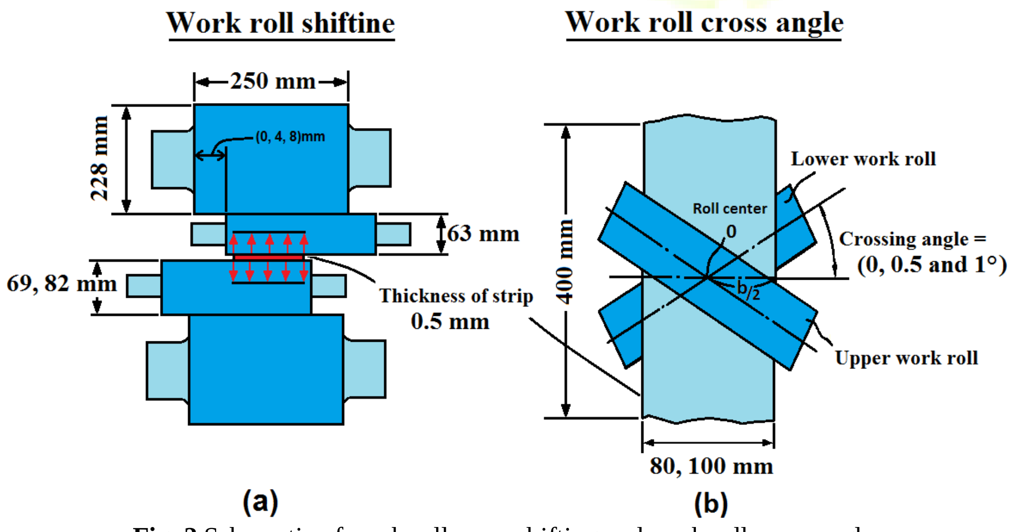
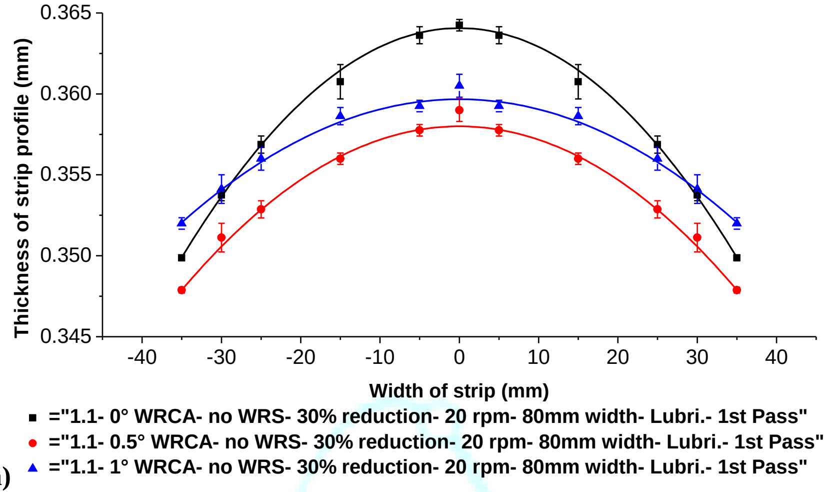
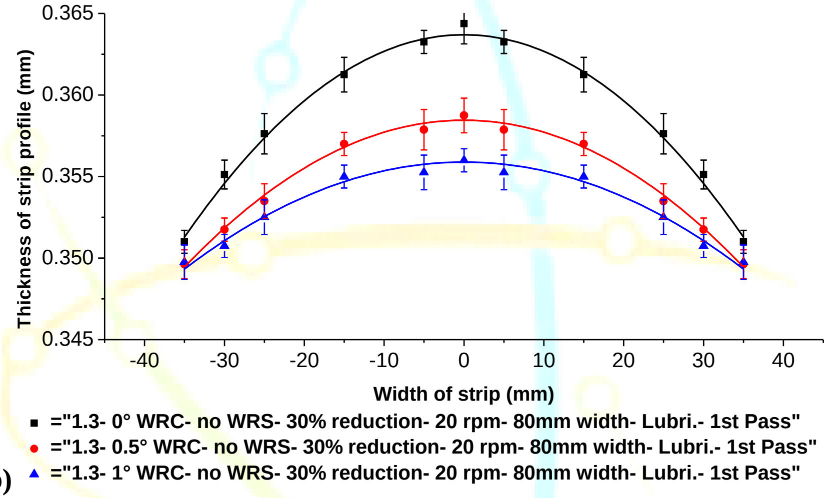


Fig. 2 Schematic of work roll cross shifting and work roll cross angle.

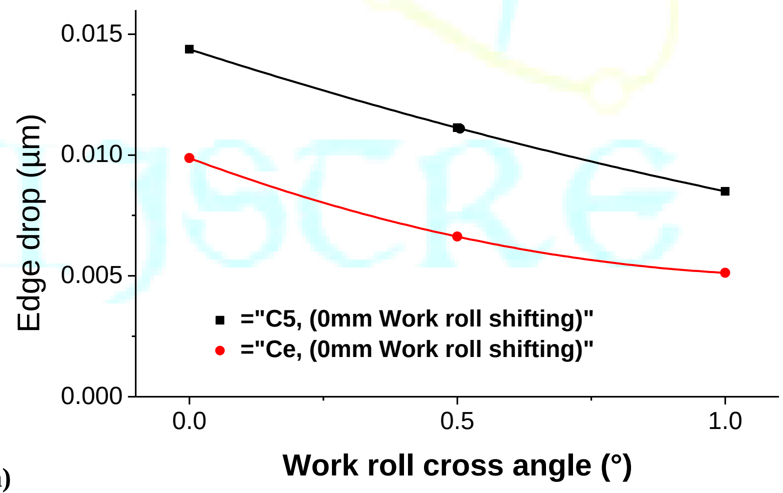


(a)

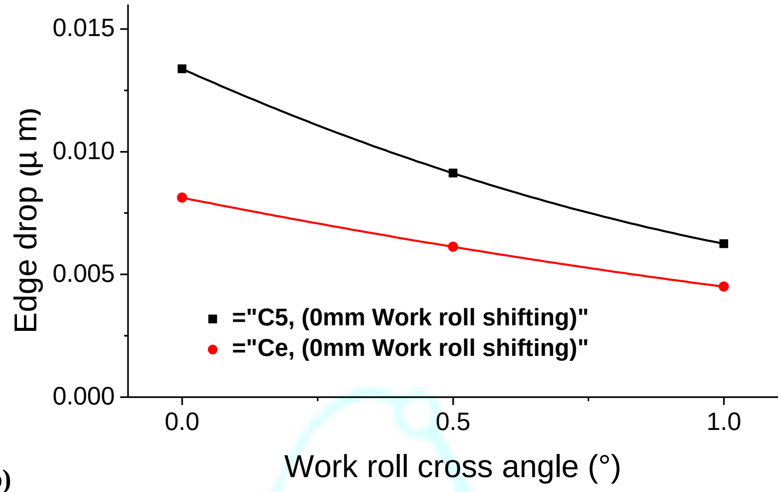


(b)

Fig. 3 Effect of work roll cross angle on strip profile at **(a) speed ratio 1.1, (b) speed ratio 1.3**– 1st pass.



(a)



(b)

Fig. 4 Effect of work roll cross angle on strip crown and edge drop at **(a) speed ratio 1.1,** and **(b) speed ratio1.3**– 1st pass.

(a)

(b)

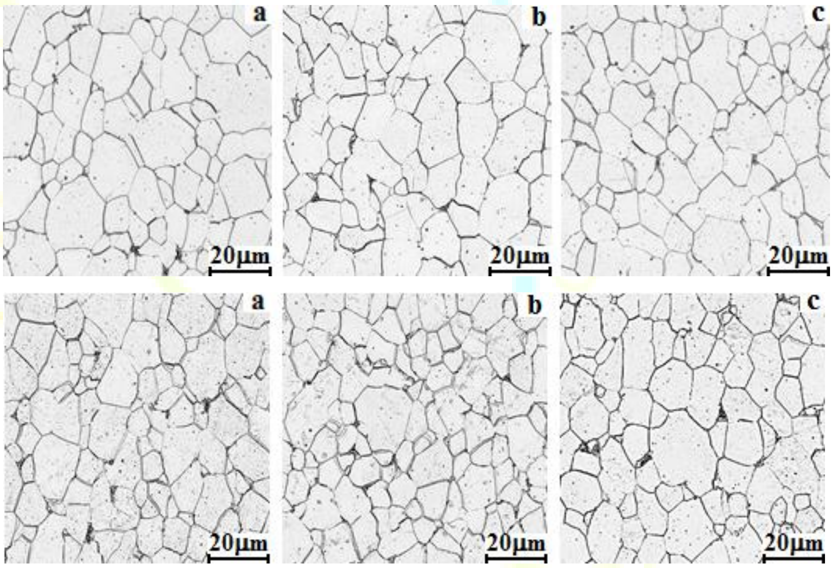
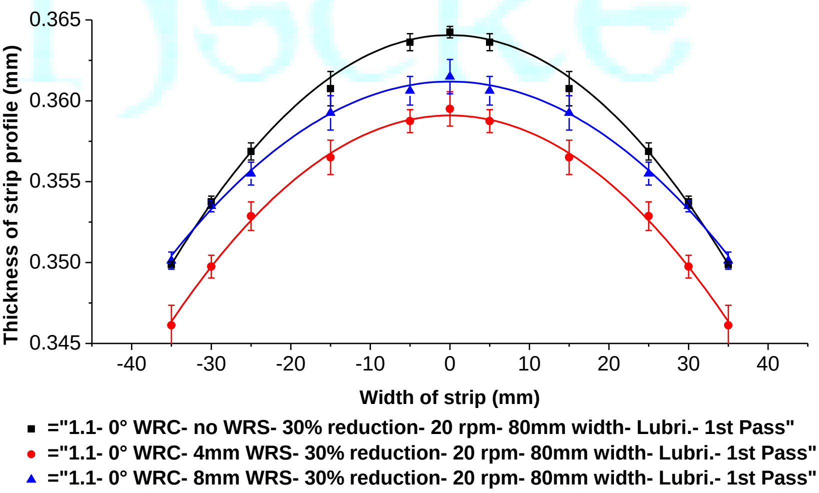
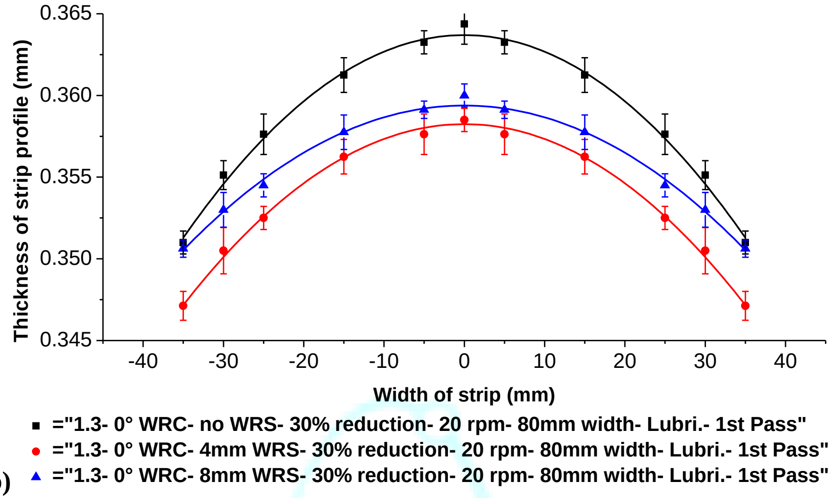


Fig. 5 Cross section microstructure of rolled strip for **(a) speed ratio 1.1, and (b) speed ratio 1.3**, 80.0mm width, 30.0rpm, 20.0% reduction and no work roll shifting and work roll cross angles: (a) 0° , (b) 0.5^{o} and (c) 1.0^{o} – Lubricated- 1st Pass.



(a)



(b)

Fig. 6 Effect of work roll shifting value on strip profile at **(a) speed ratio 1.1, and (b) speed ratio 1.3**– 1st pass.

(a)

(b)

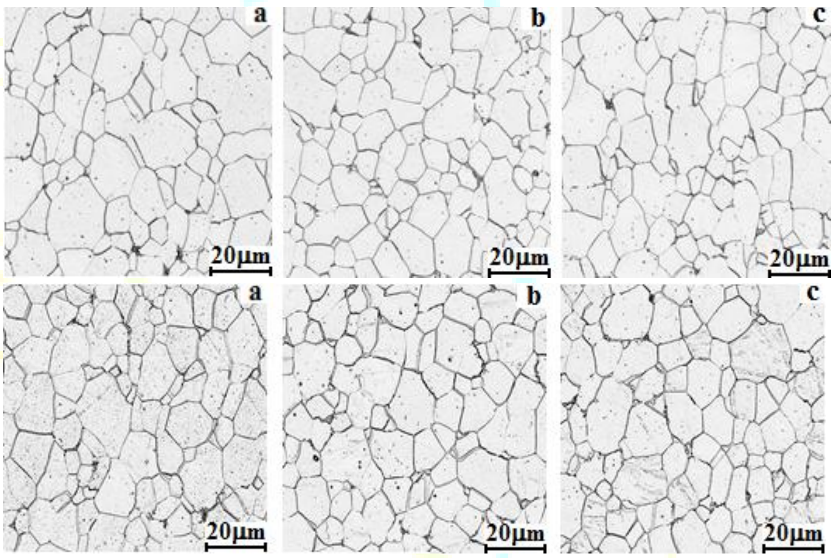
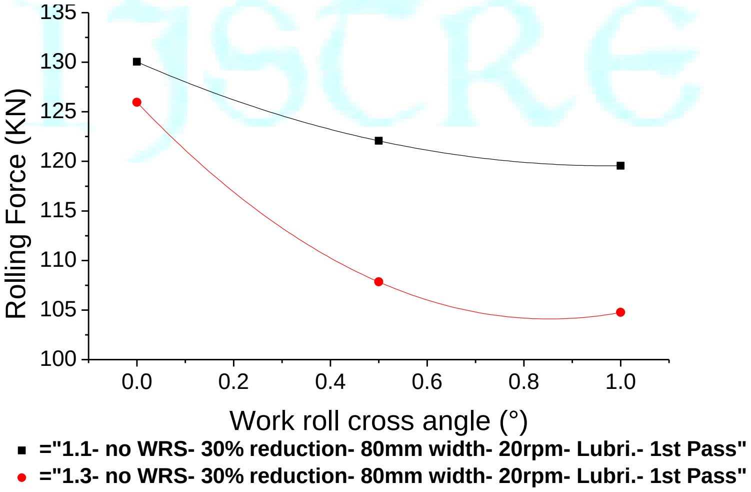
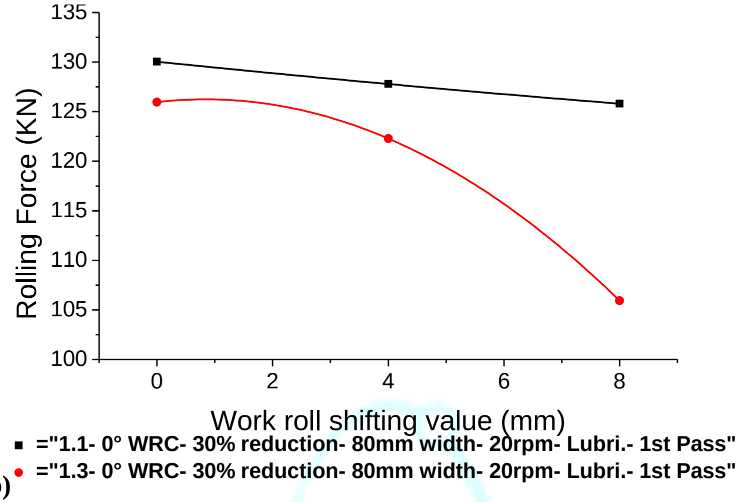


Fig. 7 Cross section microstructure of rolled strip for **(a)speed ratio 1.1, and (b) speed ratio 1.3**, 80.0mm width, 30.0rpm, 20.0% reduction and **no work roll cross angle** and work roll cross angles: (a) 0 , (b) 4.0mm and (c) 8.0mm – Lubricated- 1st Pass.

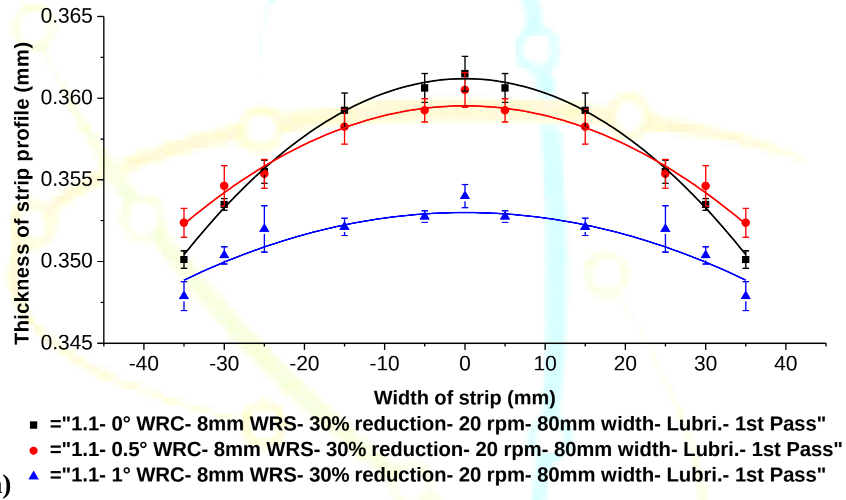


(a)

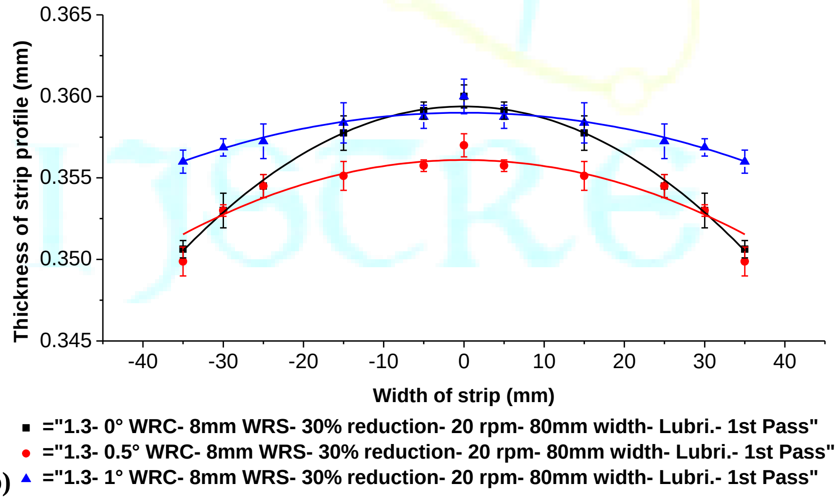


(b)

Fig. 8 Effect of (a) work rolls cross angle, and (b) work roll shifting value on rolling force at **speed ratio 1.1 vs 1.3**– 1st pass.

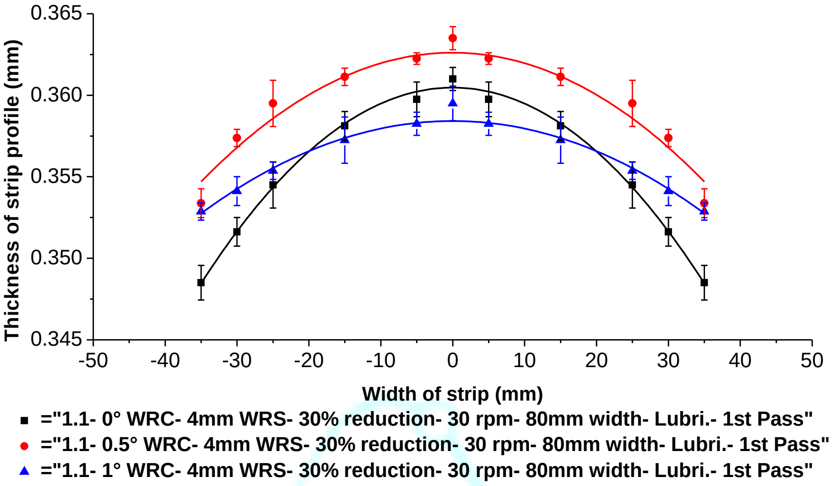


(a)



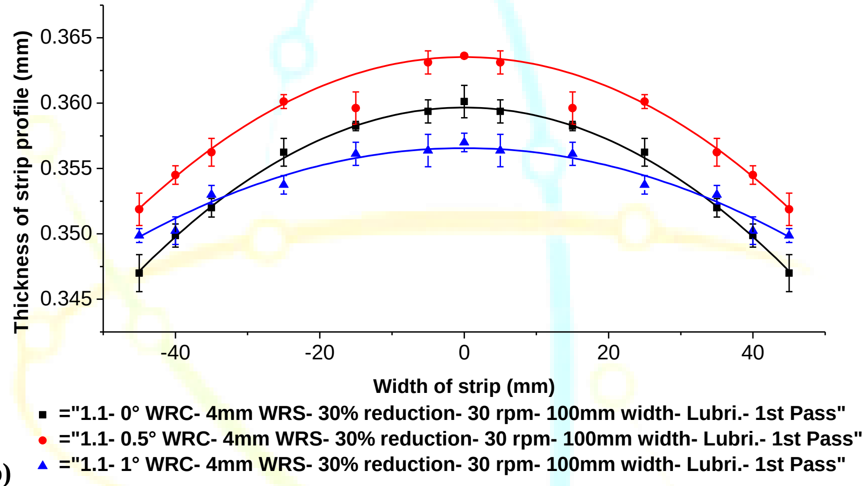
(b)

Fig. 9 Combined effect of work roll cross angle and work roll shifting value on strip profile at **(a) speed ratio of 1.1, and (b) speed ratio of 1.3** – 1st pass.



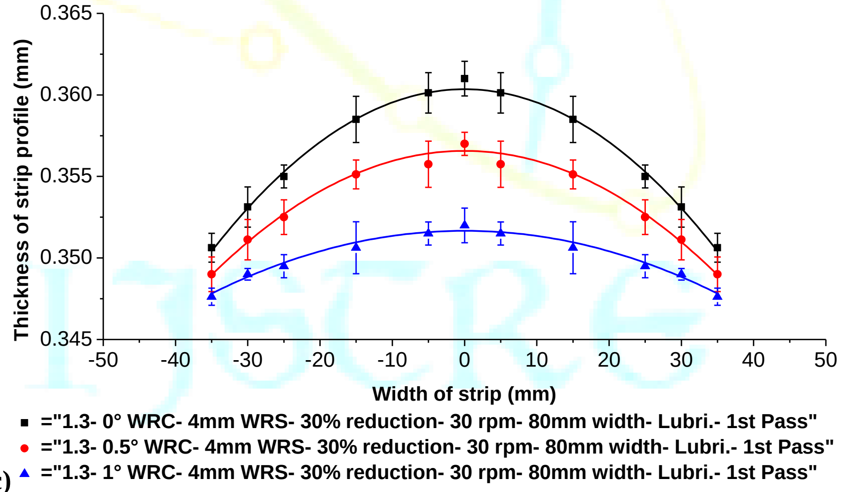
0.365
0.360
0.355
0.350
0.345
Thickness of strip profile (mm)
-50
-40
-30
-20
-10
0
10
20
30
40
50
Width of strip (mm)
="1.1- 0° WRC- 4mm WRS- 30% reduction- 30 rpm- 80mm width- Lubri.- 1st Pass"
="1.1- 0.5° WRC- 4mm WRS- 30% reduction- 30 rpm- 80mm width- Lubri.- 1st Pass"
="1.1- 1° WRC- 4mm WRS- 30% reduction- 30 rpm- 80mm width- Lubri.- 1st Pass"

(a)



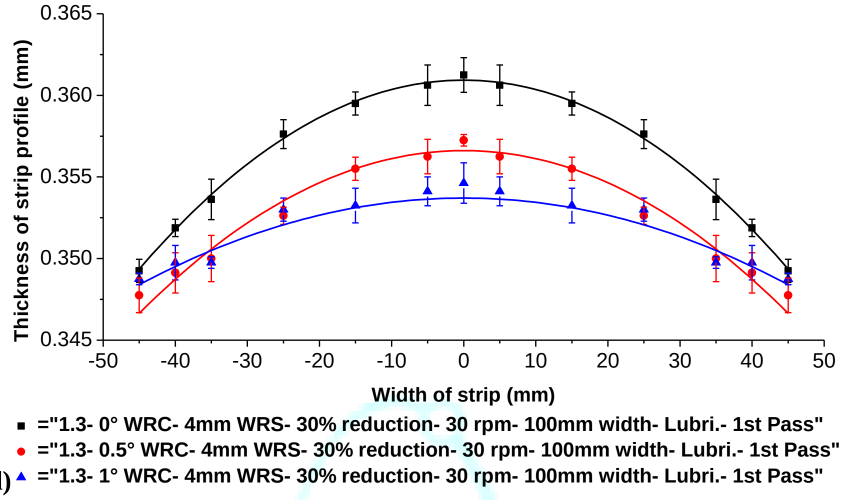
0.365
0.360
0.355
0.350
0.345
Thickness of strip profile (mm)
-40
-20
0
20
40
Width of strip (mm)
="1.1- 0° WRC- 4mm WRS- 30% reduction- 30 rpm- 100mm width- Lubri.- 1st Pass"
="1.1- 0.5° WRC- 4mm WRS- 30% reduction- 30 rpm- 100mm width- Lubri.- 1st Pass"
="1.1- 1° WRC- 4mm WRS- 30% reduction- 30 rpm- 100mm width- Lubri.- 1st Pass"

(b)



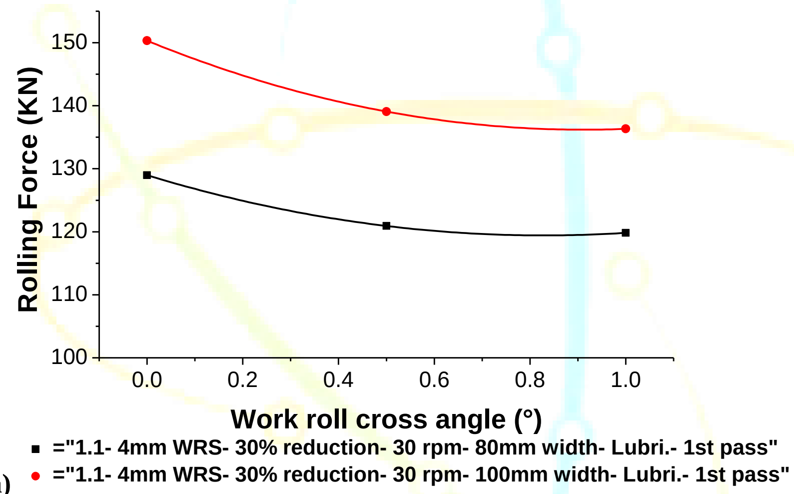
0.365
0.360
0.355
0.350
0.345
Thickness of strip profile (mm)
-50
-40
-30
-20
-10
0
10
20
30
40
50
Width of strip (mm)
="1.3- 0° WRC- 4mm WRS- 30% reduction- 30 rpm- 80mm width- Lubri.- 1st Pass"
="1.3- 0.5° WRC- 4mm WRS- 30% reduction- 30 rpm- 80mm width- Lubri.- 1st Pass"
="1.3- 1° WRC- 4mm WRS- 30% reduction- 30 rpm- 80mm width- Lubri.- 1st Pass"

(c)

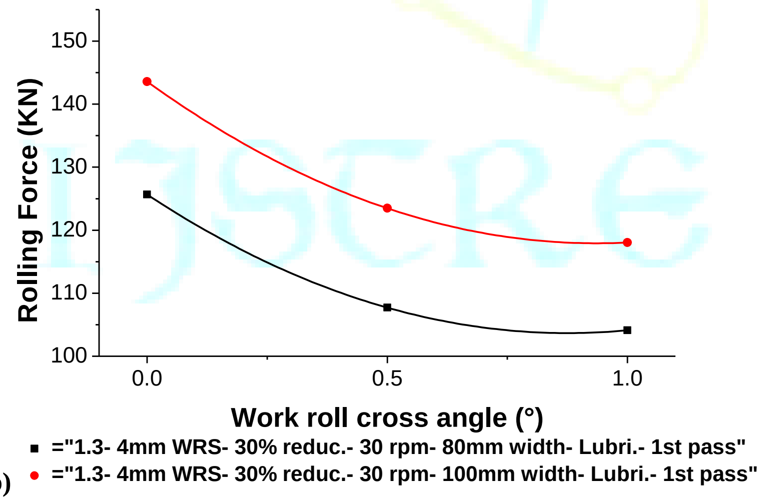


(d)

Fig. 10 Strip profile for **(a) 80mm, and (b) 100mm**, widths at speed ratio of 1.1, and (c) 80.0mm, and (d) 100.0mm , widths at speed ratio of 1.3 – 1st pass

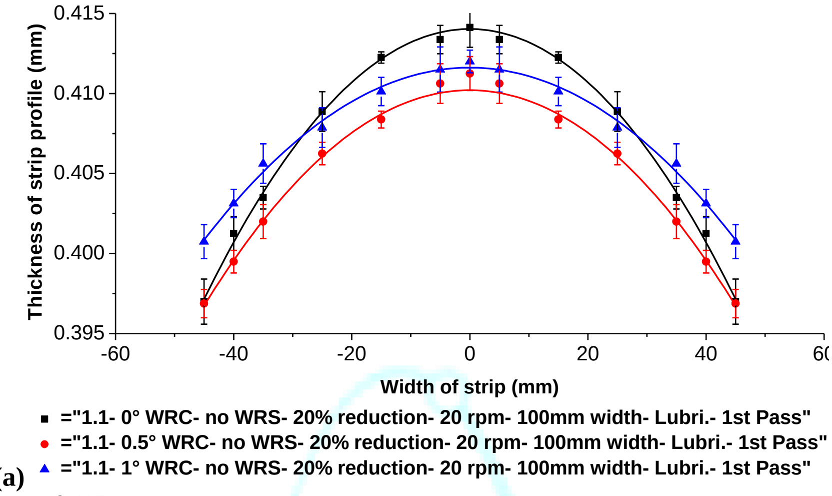


(a)



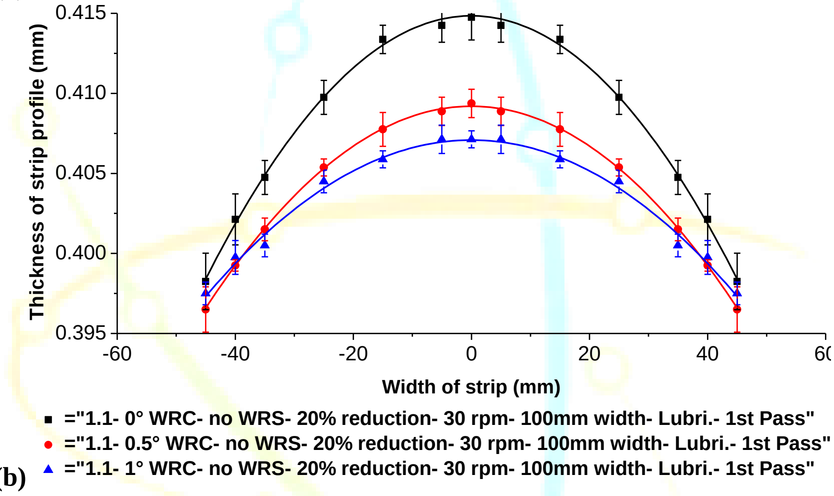
(b)

Fig.11 Effect of width on rolling force at **(a) speed ratio of 1.1, and (b) speed ratio of 1.3**– 1st pass.



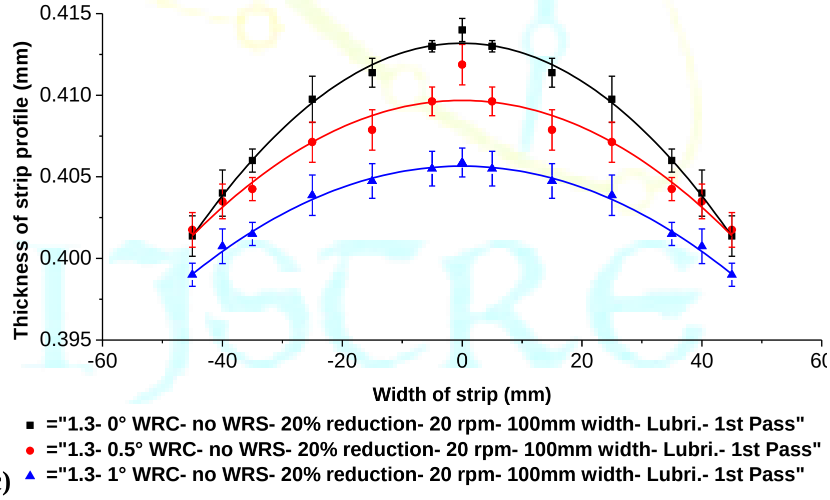
Thickness of strip profile (mm)
Width of strip (mm)
="1.1- 0° WRC- no WRS- 20% reduction- 20 rpm- 100mm width- Lubri.- 1st Pass"
="1.1- 0.5° WRC- no WRS- 20% reduction- 20 rpm- 100mm width- Lubri.- 1st Pass"
="1.1- 1° WRC- no WRS- 20% reduction- 20 rpm- 100mm width- Lubri.- 1st Pass"

(a)



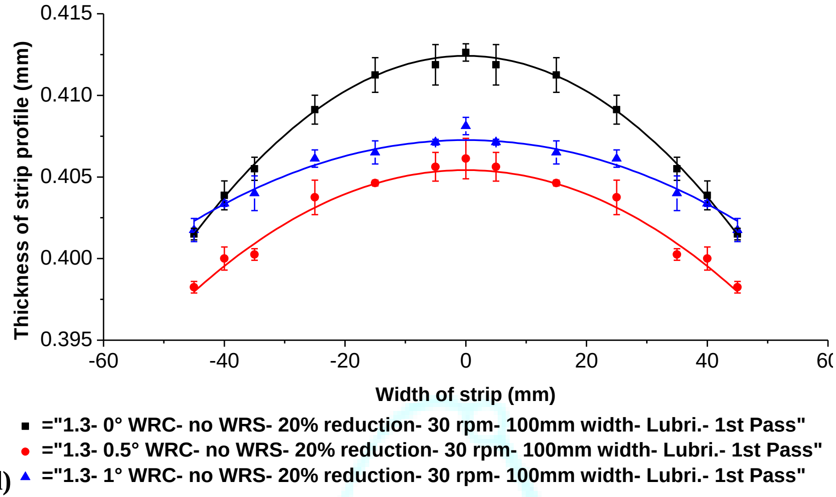
Thickness of strip profile (mm)
Width of strip (mm)
="1.1- 0° WRC- no WRS- 20% reduction- 30 rpm- 100mm width- Lubri.- 1st Pass"
="1.1- 0.5° WRC- no WRS- 20% reduction- 30 rpm- 100mm width- Lubri.- 1st Pass"
="1.1- 1° WRC- no WRS- 20% reduction- 30 rpm- 100mm width- Lubri.- 1st Pass"

(b)



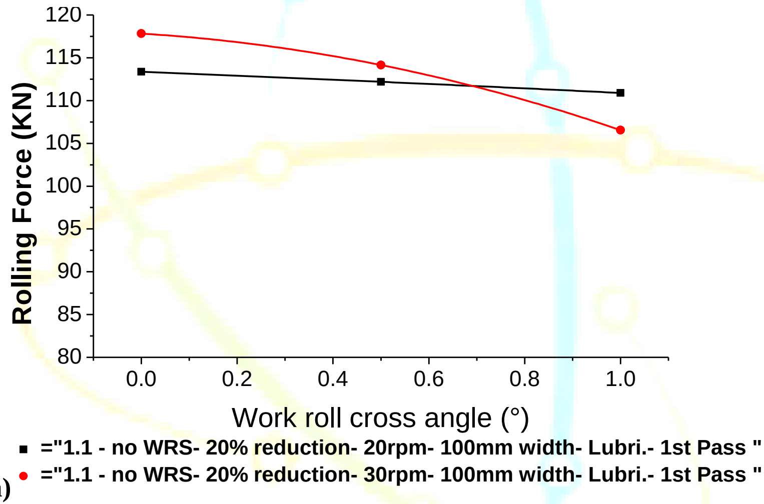
Thickness of strip profile (mm)
Width of strip (mm)
="1.3- 0° WRC- no WRS- 20% reduction- 20 rpm- 100mm width- Lubri.- 1st Pass"
="1.3- 0.5° WRC- no WRS- 20% reduction- 20 rpm- 100mm width- Lubri.- 1st Pass"
="1.3- 1° WRC- no WRS- 20% reduction- 20 rpm- 100mm width- Lubri.- 1st Pass"

(c)

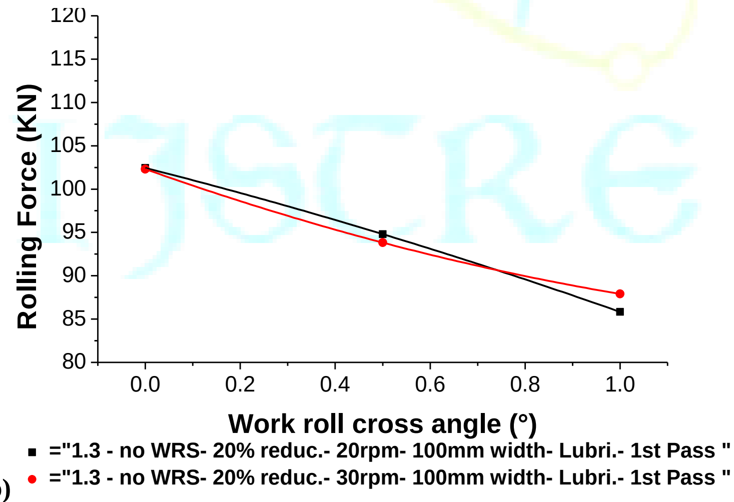


(d)

Fig. 12 Strip profile at rolling speed of **(a) 20.0rpm, and (b) 30.0rpm** at speed ratio 1.1, and **(c) 20.0rpm**, and **(d) 30.0rpm** at speed ratio 1.3– 1st pass.

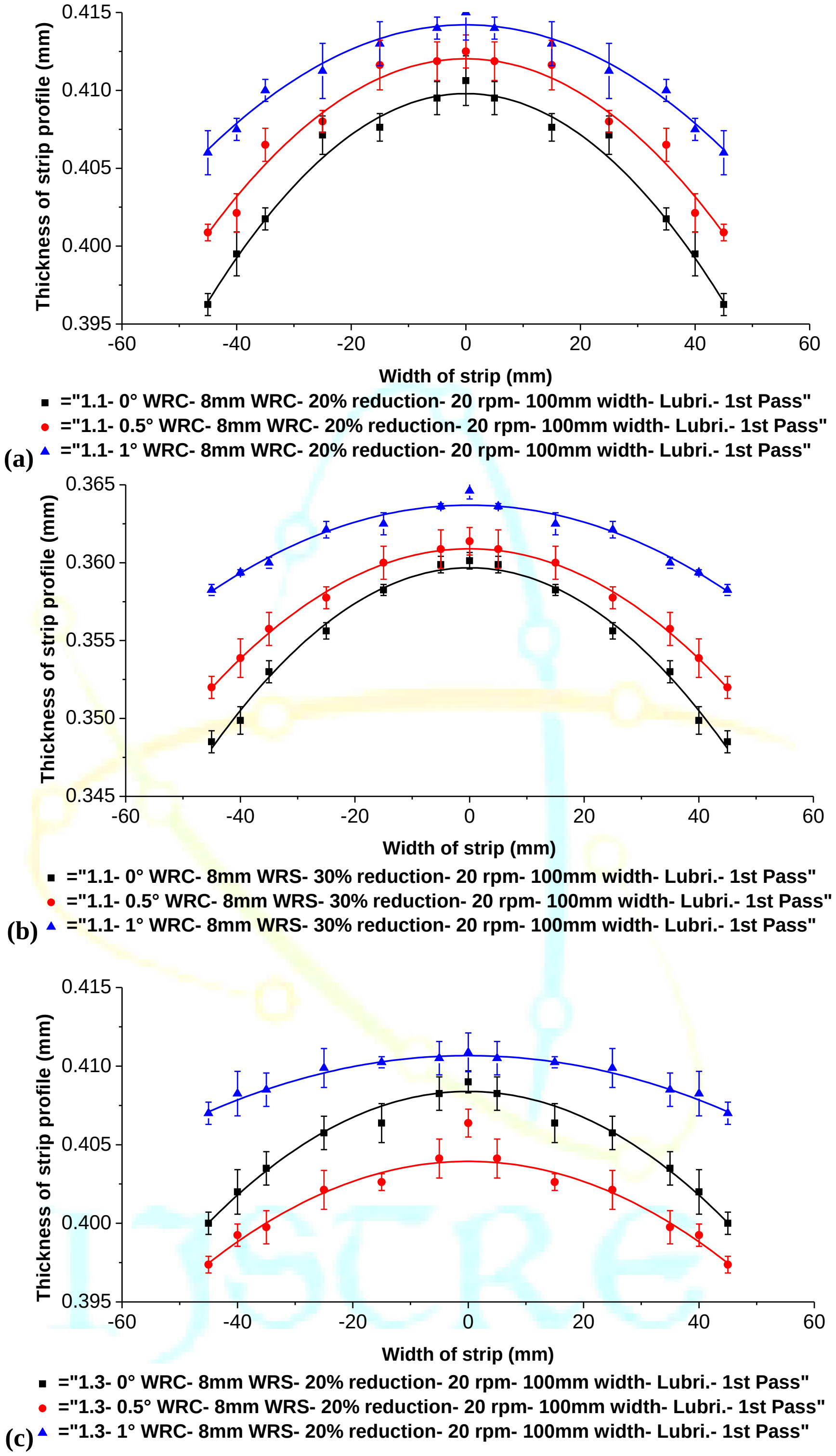


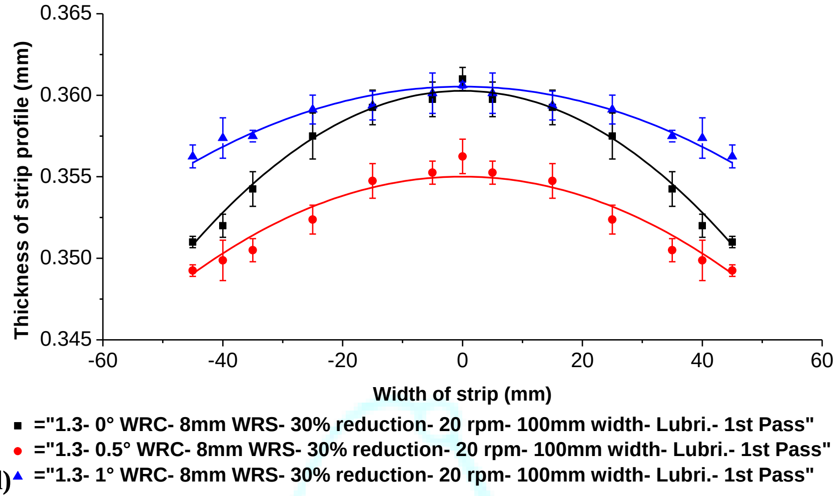
(a)



(b)

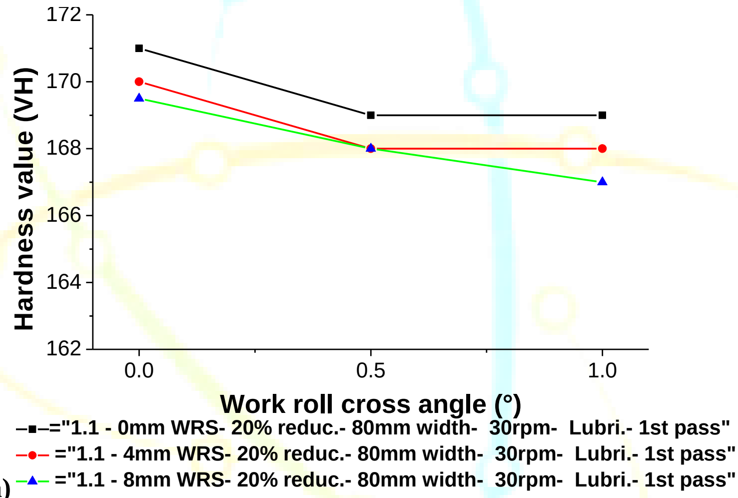
Fig. 13 Effect of rolling speed on rolling force at **(a) speed ratio1.1, and (b) speed ratio 1.3** – 1st pass


Thickness of strip profile (mm)
Width of strip (mm)
■ ="1.1- 0° WRC- 8mm WRC- 20% reduction- 20 rpm- 100mm width- Lubri.- 1st Pass"
● ="1.1- 0.5° WRC- 8mm WRC- 20% reduction- 20 rpm- 100mm width- Lubri.- 1st Pass"
▲ ="1.1- 1° WRC- 8mm WRC- 20% reduction- 20 rpm- 100mm width- Lubri.- 1st Pass"
(a)
Thickness of strip profile (mm)
Width of strip (mm)
■ ="1.1- 0° WRC- 8mm WRS- 30% reduction- 20 rpm- 100mm width- Lubri.- 1st Pass"
● ="1.1- 0.5° WRC- 8mm WRS- 30% reduction- 20 rpm- 100mm width- Lubri.- 1st Pass"
▲ ="1.1- 1° WRC- 8mm WRS- 30% reduction- 20 rpm- 100mm width- Lubri.- 1st Pass"
(b)
Thickness of strip profile (mm)
Width of strip (mm)
■ ="1.3- 0° WRC- 8mm WRS- 20% reduction- 20 rpm- 100mm width- Lubri.- 1st Pass"
● ="1.3- 0.5° WRC- 8mm WRS- 20% reduction- 20 rpm- 100mm width- Lubri.- 1st Pass"
▲ ="1.3- 1° WRC- 8mm WRS- 20% reduction- 20 rpm- 100mm width- Lubri.- 1st Pass"
(c)

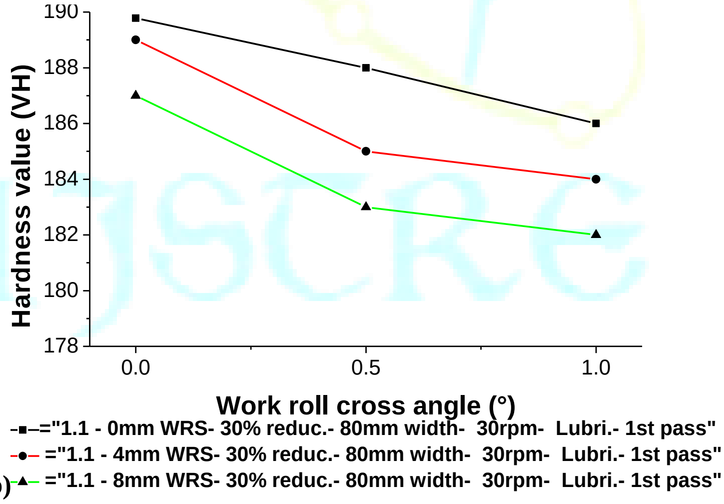


(d)

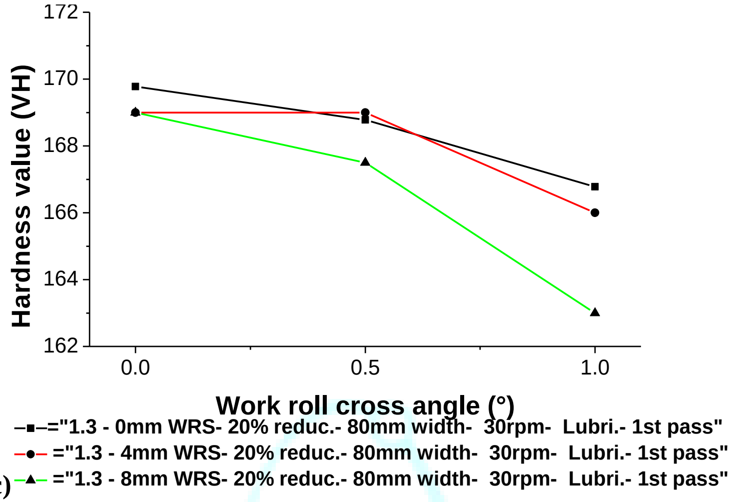
Fig. 14 Strip profile at **(a) 20.0%**, and (b) **30.0%** reduction at speed ratio 1.1, and **(c) 20.0%, and (d) 30.0% reduction**, at speed ratio 1.3 – 1st pass.



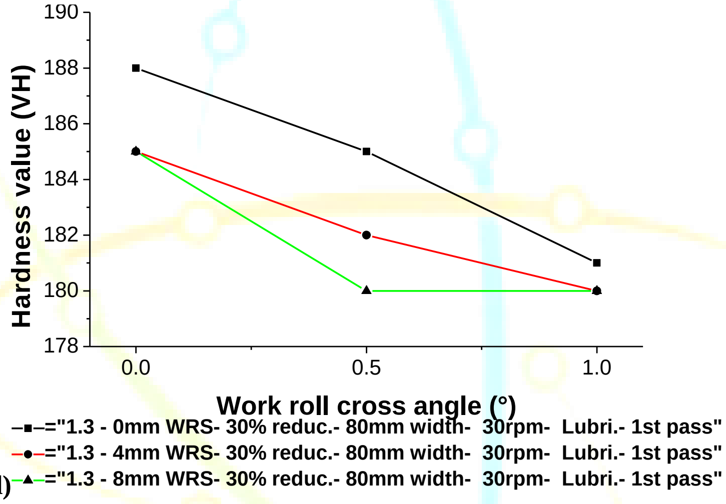
(a)



(b)

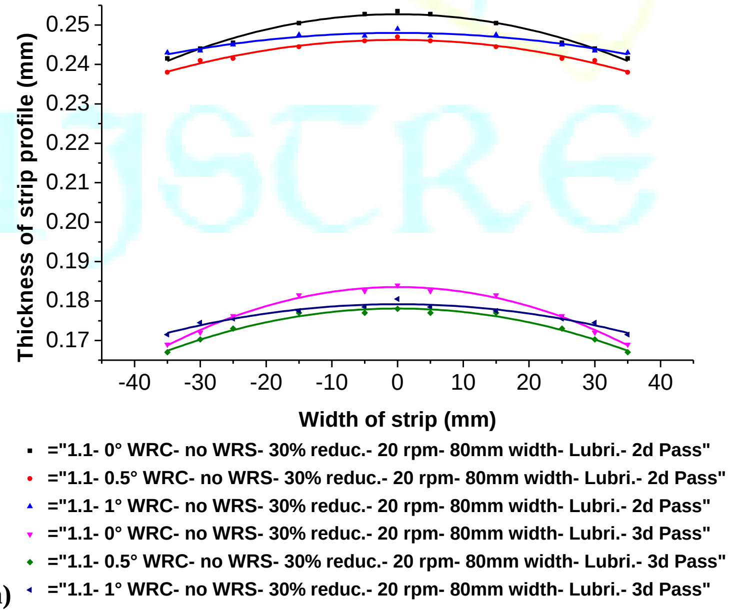


(c)

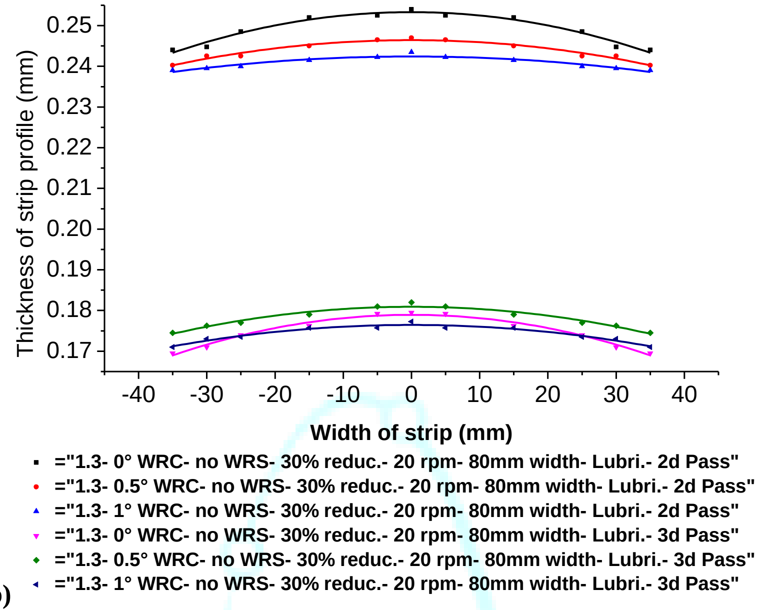


(d)

Fig. 15 Strip hardness at **(a) 20.0%** reduction, and **(b) 30.0%** reduction at 1.1 speed ratio and, **(c) 20.0%** reduction, and **(d) 30.0%** reduction at 1.3 speed ratio – 1st pass.

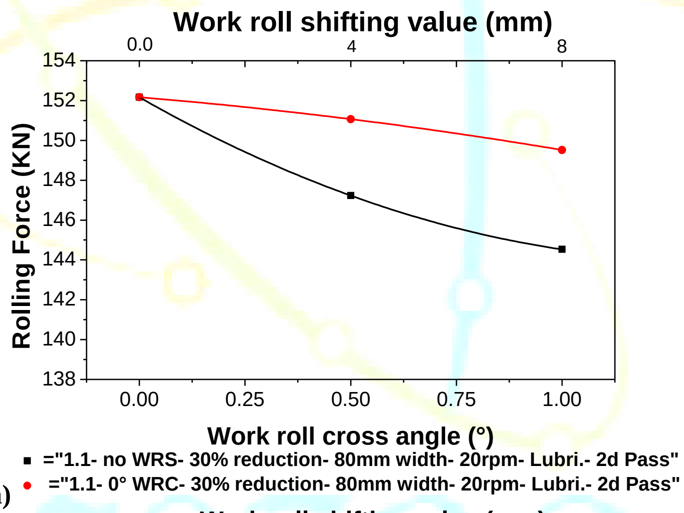


(a)

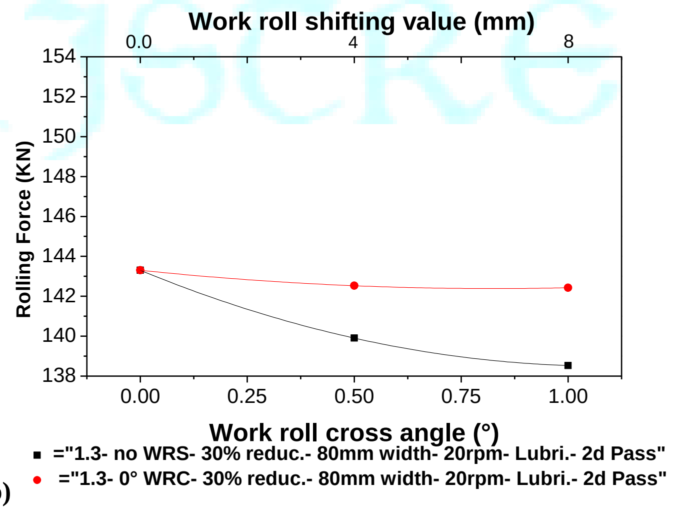


(b)

Fig. 16 Effect of work roll cross angle on strip profile at **(a) speed ratio 1.1, and (b) speed ratio 1.3** – 2ndvs3rd pass.

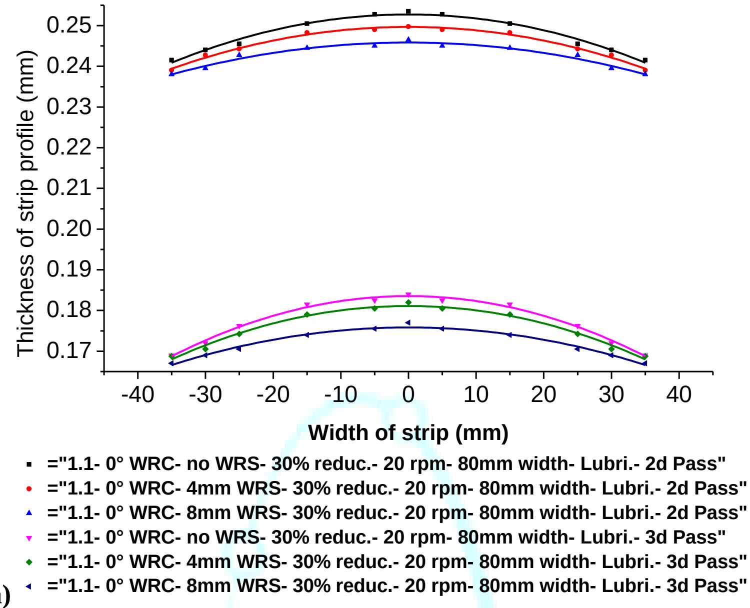


(a)

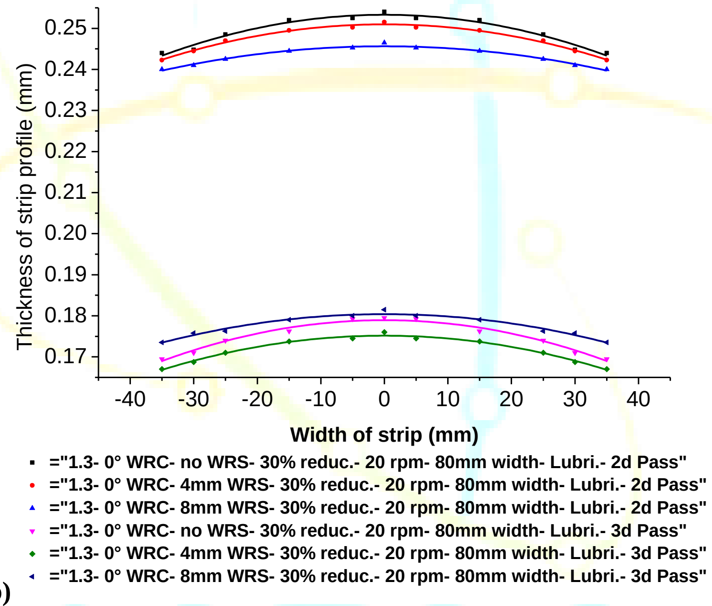


(b)

Fig. 17 Effect of work roll cross angle and wor roll shifting on rolling force at**(a) 1.1, and (b) 1.3**– 2nd pass.

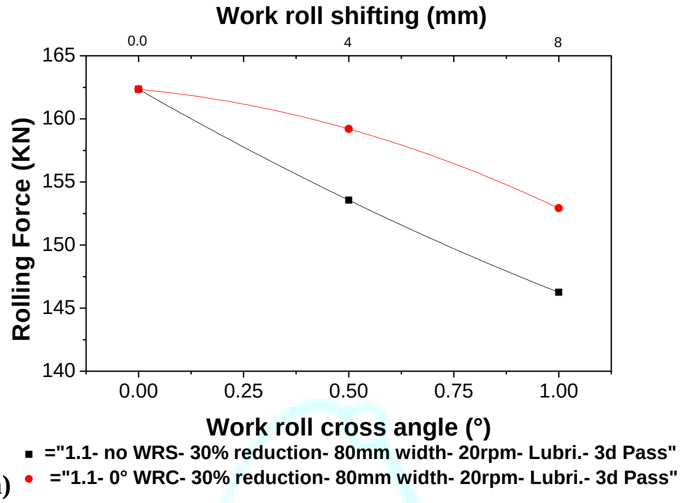


(a)

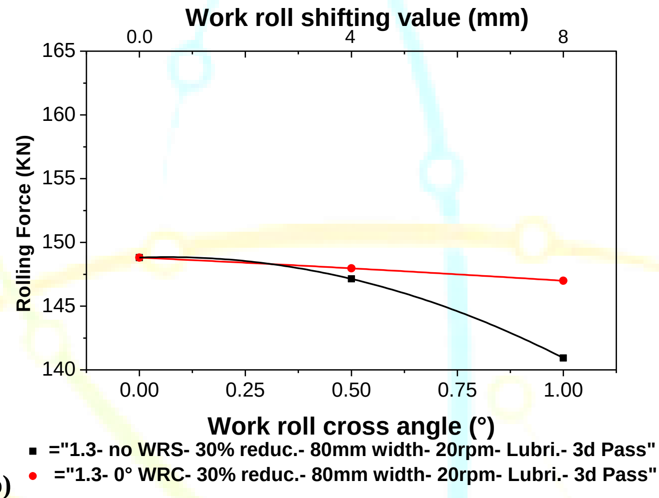


(b)

Fig. 18 Effect of work roll shifting value on strip profile at **(a) speed ratio 1.1, and (b) speed ratio 1.3** – 2ndvs3rd pass.



(a)



(b)

Fig. 19 Effect of work roll cross angle and work roll shifting on rolling force at **(a) speed ratio 1.1, and (b) speed ratio 1.3**– 3rd pass.