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MECHANICAL PROPERTIES OF ALUMINUM SHEETS AFTER ACCUMULATIVE ROLL BONDING USING TWO AND FOUR-HIGH ROLLING MILL

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ABSTRACT

This paper emphasized that there are a number of factors contributing to slightly different mechanical properties of aluminum sheets after rolling using a two or a four-high rolling mill. The major ones are the roll diameter, angular velocity, deformation zone, and surface roughness. In two-high rolling mill required annealing of the edges of the sheets, which was used to suppress the development of cracks. While higher rolling speed of the four high mill leads to higher deformation rates and a smaller deformation zone to higher pressures the in-between annealing of the edges, which was necessary on the two-high rolling mill allowed for prior precipitation evolution and therefore strengthening. The development of the oxide layer on the rolls of a two-high rolling mill was more rapid than on the rolls of a four-high rolling mill, because of relatively old and worn out surfaces, higher surface roughness as well as a bigger roll diameter. Thus, the mechanical properties of the sheets produced by a two-high and of four-high rolling mill cannot be directly compared. It is also worth pointing out that the hardness evolution of samples rolled using a two-high rolling mill preceded more quickly within the first 6 ARB cycles, but then subsided more quickly compared to a four-high rolling mill.

KEYWORDS: Two-high rolling mill, Four-high rolling mill, Accumulative Roll Bonding, Severe Plastic Deformation, Ultra-Fine Grain.

INTRODUCTION

Accumulative roll bonding is a relatively new severe plastic deformation (SPD) process, which was originally introduced and developed by Saito et al. [1,2]. The ARB process shown in figure1, involves wire brushing of metal sheet surfaces in order to remove the oxide layer, stacking of two sheets on top of each other and roll bonding them together[3,4] The two sheets are generally rolled to 50% thickness reduction and therefore leave the rolls with the original sheets thickness. During rolling the two metal sheets join together to form a solid body and once again same process repeated, wire brushed and roll bonded. The process can be repeated many number of times. In most cases, the process is repeated up to ten times.

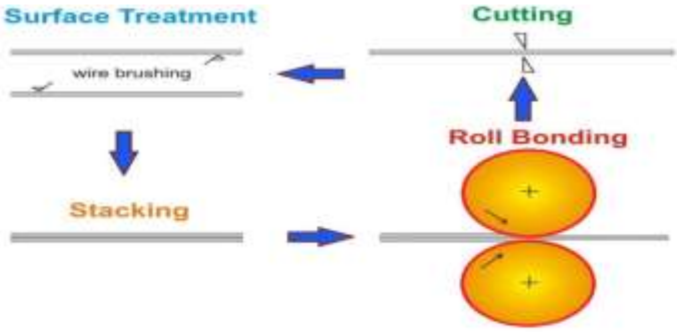

Figure: 1 Schematic illustration showing the principle of accumulative roll bonding (ARB) process.

The metal sheet deformation takes place predominantly in the rolling direction. Any increase in sheet width can be neglected since the sheets are wide enough and the broadening is prevented by high frictional resistance. During roll bonding the number of individual layers within 1mm thick sheet increases according to the power law equation (equation 1) and the thickness of the individual layers can be calculated from equation 2,

$n = 2^N$ Eq. 1

$t = \frac{t_0}{2^N}$ Eq. 2

Where n = number of individual layers
N = number of ARB cycles
t_0 = initial sheet thickness
t = final thickness of the individual layer.

Therefore, after 10 ARB cycles with 50% thickness reduction per cycle, the 1mm thick sheet develops 1024 individual layers, each having a theoretical thickness of 1µm, while the total reduction approaches 100%. Assuming Von Mises yield [5,6,7] criterion and plane strain condition i.e. no lateral spreading; the total equivalent strain after N cycles can be calculated according to the equation 3, [8,9] as shown in figure 2.

$$\varepsilon_{tot} = \left\{\frac{2}{\sqrt{3}} \cdot In\left(\frac{1}{2}\right)\right\} \cdot N = 0.80 \cdot N$$

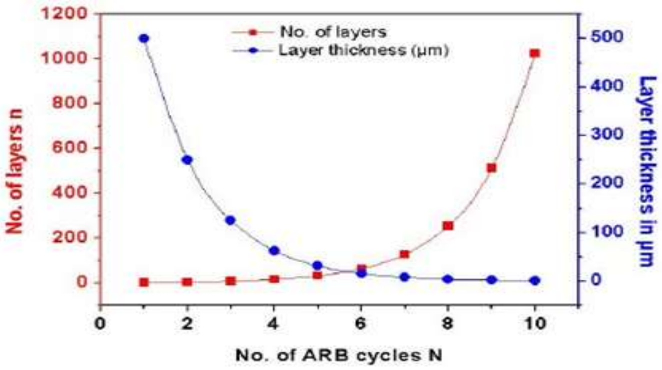

Figure 2 a): Geometrical changes of the materials during ARB where 2 metals sheets 1mm thick are roll bonded by 50% thickness reduction per cycle [10,11].

EXPERIMENTAL PROCEDURE

The Accumulative Roll Bonding (ARB) Process belongs to a group of severe plastic deformation (SPD) techniques used to develop ultrafine-grained or nano-structured sheets by applying repeated rolling, which leads to high levels of shear strain throughout the sheet thickness. The surface of one millimeter thick and 50-100 mm wide metal strips were preliminary wire brushed in order to remove oxide layer for better interlamellar bonding of sheets, and subsequently folded or stacked on top of each other and rolled together without lubrication using a two-high rolling mill (Vaid Engineering Industries, New Delhi, roller diameter: Ø = 135 mm) or a four-high rolling mill (Vaid Engineering Industries, New Delhi; roller diameter: Ø = 30 mm). The process was then repeated a number of times. The roll diameter and the peripheral roll speed of the four-high rolling mill average 30 mm and 80 revs/min, respectively. The most important ARB process parameters include the initial state of the material, process temperature, thickness reduction and the number of rolling cycles N. Commercial purity aluminum AA1050and aluminum alloys AA6016 were solutionised before the ARB process in order to obtain a defined reference material. The initial state of the material and the ARB parameters are listed in table 1.

Table 1: Initial states of material prior to rolling and the corresponding ARB process parameters

Material	thickness reduction	State before Initial Preheating	ARB cycles	Sheet Thickness	Operating Temp.
AA1050	50%	Solutionised (520^0 C/1 h) water quenched	8-10	1 mm	Room Temp.
AA6016	50%	Solutionised (520^0 C/1 h) water	8-10	1mm	180^0 C, 200^0 C, 250^0 C

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Depending on the type of material being processed, the process temperature varied between 200^{o}C-350^{o}C and the minimum amount of thickness reduction averaged 50%. Rolling at elevated temperatures involved pre warming of metal sheets in a furnace for a couple of minutes before rolling. All samples were air cooled before repeating the process. The maximum number of ARB cycles of each material is generally dependent on the initial strength of the material, the development of the UFG microstructure and the achievable saturation in strength. The process was usually completed after the UFG microstructure has been developed and the saturation in strength was reached. At the beginning the rolling mill used for the ARB process was a two-high rolling mill. The maximum width of metal strips produced without severe cracking at the edge was approximately 50 mm wide. In order to improve and optimize the process as well manufacture wider metal sheets, a four-high rolling mill was acquired.

RESULT AND DISCUSSION

The most important technical characteristics of the both types of rolling mills, which influence the quality of the surface and the mechanical properties of the metal sheets are the roll diameter and hence the projected length of arc of contact, i.e. the deformation zone, as well as the roll speed and the surface of the rolls.

The first accumulative roll bonding tests were carried out on commercial purity aluminum AA1050 using a two-high rolling mill which strongly restricted the final perpendicular to the rolling direction prior to roll bonding the edges of the sheets used to be heat treated using a welding torch in order to relieve the stresses and avoid crack propagation further across the sheet. The front and end edges of the sheets were also mechanically joined together using small studs in order to avoid shearing of the sheets during rolling furthermore the two-high rolling mill rolls used for the first experiment had relatively quality of the rolled sheets the two top examples in figure 3 show AA1050 and AA6016 aluminum sheets with a lot cracking at the edges and a dull and rough surface finish

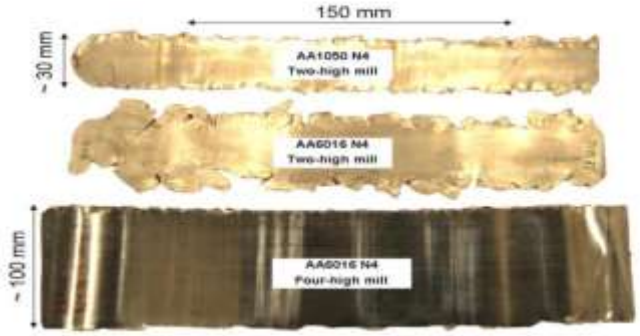

Figure 3: Surface finish and aluminum sheet width improvement of commercial purity aluminum AA1050and aluminum alloy AA6016 by roll bonding using a four high rolling mill.

With an intention to improve the process a four-high rolling mill was acquired. This contributed not only to the improvement of the final width of the sheets up to 100mm as shown in figure 3, but also to the quality of the surface. The variation in thickness along the length of the sheet was reduced as shown in figure 4 and the surface of the sheets became smoother figure 5. The overall deformation became more homogeneous, the crack development was retarded due to smaller deflection of the rolls during the process and the annealing of edges between each ARB cycle was no longer necessary.

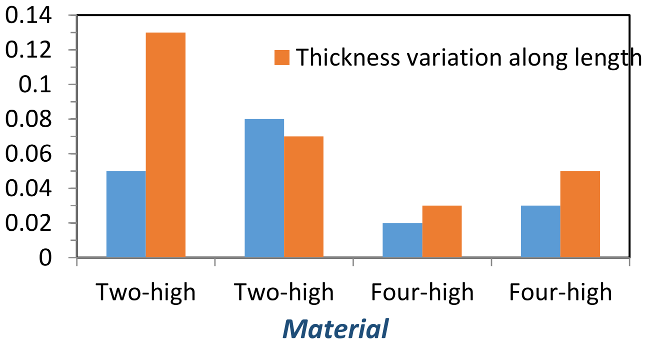

Figure 4: Variation in sheet thickness of aluminum alloys AA1050 and AA6016

Table 2 Variation in sheet thickness of aluminium alloys AA1050 and AA6016.

S. No.		**Thickness variation along width**	**Thickness variation along length**
1.	**Two-high AA1050**	0.05	0.13
2.	**Two-high AA6016**	0.08	0.07
3.	**Four-high AA1050**	0.02	0.03
4.	**Four-high AA6016**	0.03	0.05

The improvement of bonding between individual aluminum sheets was also investigated as a part of the ARB process improvement. After different surface treatments, including sand blasting, grinding and wire brushing, it was found that the best bonding can be achieved with the roughest surfaces. In addition to that, the quality of the ARB surfaces was analyzed by measuring the surface roughness of the sheets produced by a two-high and a four-high rolling mill. From figure 5, it can be seen that the surface roughness of the sheets rolled using the four-high rolling mill is significantly lower. Thus, smaller roll diameter or higher rolling pressure leads to an overall better surface quality.

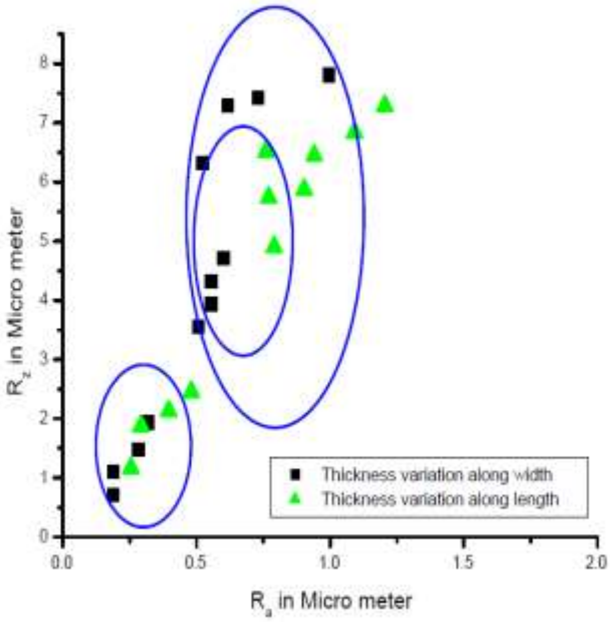

Figure 5: Quality improvement of the metal sheet surfaces by means of a four-high rolling mill. Micro meter

Another parameter that plays an important role in the improvement of the ARB process is the process temperature. Aluminum all AA6016 was always roll bonded at elevated temperatures due to its higher hardness. Roll bonding at various process temperatures was performed and the difference in hardness evolution can be seen in figure 6 for three temperatures: 180ºC, 230ºC and 250ºC. The highest hardness values were achieved by roll bonding at 180ºC, due to slower dynamic recovery. Higher temperatures decreases the potential for a rapid grain refinement and lead to material softening as a result of dynamic recovery and /or partial recrystallisation during per-heating and rolling.

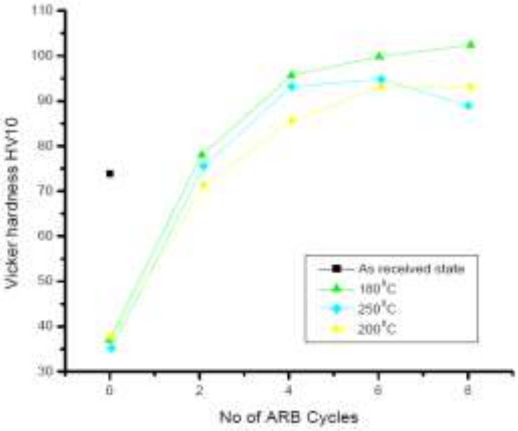

Figure 6: Hardness evolution at various process temperature of the aluminum alloy AA6016 with an increasing number of ARB cycles.

However, roll bonding of individual sheets at 180ºC was not satisfactory. The SEM micrograph in figure 7-a, shows aluminum alloy AA6016 after 5 ARB cycle and confirms poor bonding between the sheets at low process temperatures ranging between 180ºC–200ºC. On the other hand, roll bonding at higher temperatures of 250ºC results in premature thermal instability, but a better bonding between sheets in figure 7 b. As a result, the ARB process was generally carried out at the intermediate temperature of 230ºC in order to obtain a compromise between good thermal stability and good bonding between sheets.

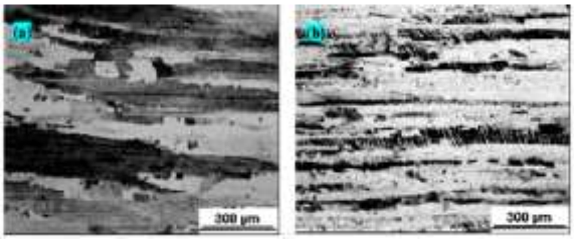

Figure 7: SEM micrographs showing interlamellar bonding of AA6016 after 5 ARB cycles at a) 200°C and b) 250ºC process temperature.

It must be emphasized that there are a number of factors contributing to slightly different mechanical properties of aluminum sheets after rolling using a two or a four-high rolling mill as shown in 8. The major ones are the roll diameter (two-high rolling mill, 130 mm diameter; four high rolling mill, 32mm diameter) and thus the angular velocity as well as the deformation zone of the rolls and surface roughness. In addition rolling with a two-high rolling mill required annealing of the edges of the sheets, which was used to suppress the development of cracks. While higher rolling speed of the four high mill leads to higher deformation rates and a smaller deformation zone to higher pressures the in-between annealing of the edges, which was necessary on the two-high rolling mill allowed for prior precipitation evolution and therefore strengthening

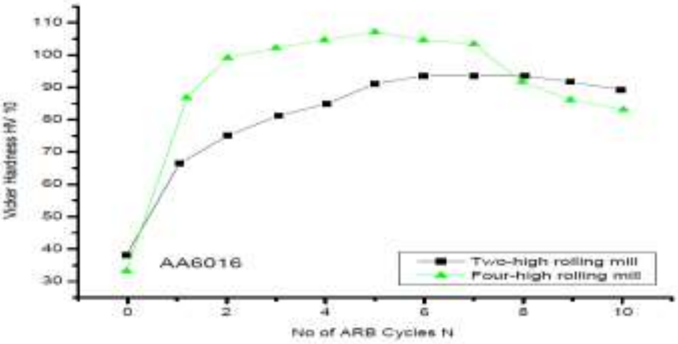

Figure 8: Comparison of the hardness evolution between the two high and the four-high rolling mill (AA6016rolled at 230ºC)

High surface roughness of the sheets and the rapid build–up of the oxide layer during rolling also affect the hardness values and evolution. It show that hardness of the ARB sheets increased with an increasing thickness of the oxide layer on the rolls. The development of the oxide layer on the rolls of a two-high rolling mill was more rapid than the rolls of a four-high rolling mill, because of relatively old and worn out surfaces, higher surface roughness as well as a bigger roll diameter. Thus, the mechanical properties of the sheets produced by a two-high and of four-high rolling mill cannot be directly compared. It is also worth pointing out that the hardness evolution of samples rolled using a two-high rolling mill preceded more quickly within the first 6 ARB cycles, but then subsided more quickly compared to a four-high rolling mill.

CONCLUSION

The ARB process optimization was predominantly carried out on commercial pure aluminum AA1050. With specifically targeted testing techniques, adapted process parameters and the acquisition of a four-high rolling mill, the ARB process was scaled up, optimized and the quality of the sheets was improved. The ARB process was significantly shortened and it became more robust. The deformation during rolling became more homogeneous, cracking of the edges was eliminated and crack propagation was suppressed. These factors cumulatively contributed to less material waste during the process. The surface quality was considerably improved and the sheet thickness became more homogeneous. The contribution of a four-high rolling mill was especially manifested in terms of the final width of the metal sheets, which was improved up to 100 nm. Further increase of the width of the sheets was not possible due to the restricting width of the rollers.

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