Impact of hot rolling on the r-values of 6000 series aluminium alloys

SARBAN Ali A.[1,a]

[1] Aluminium Duffel BV, A . Stocletlaan 87, 2570 Duffel, Belgium

[a]ali.sarban@aluminiumduffel.com

Keywords: Aluminium, 6000 Series, Hot Rolling, R-Values, Rolling Speed, Rolling Temperature

Abstract. Crystallographic texture of sheet metal influences formability significantly. Lankford coefficient or the so-called r-value, a texture related property, is a property often specified as a customer requirement and therefore a property that requires close monitoring and control during the production process. Through systematic experiments, it is demonstrated how hot rolling, especially hot tandem rolling influences r-values of wrought aluminium alloys. A tandem rolling model has been developed that enables control of final r-value for a given 6016 alloy with a given downstream process. The model clearly shows how entry temperature and exit speed of tandem mill can be used to control the final product's r-value. The model that provides a metallurgical explanation for the effect, can be used to steer the tandem mill in such a manner that a minimum r-value is guaranteed and at the same time, variations of r-value along the length of the strip are minimized or suppressed. The model also provides a better alternative to the existing and conventional tandem mill steering methodology based on constant exit temperature. The proposed methodology is based on keeping a (nearly) constant Zener-Hollomon parameter along the length of the strip during tandem rolling.

Introduction

Continuously increasing demands on reducing CO_2 emission has significantly increased the use of Aluminum alloys in car body applications. 6000 series aluminum alloys have received special attention due to excellent combination of mechanical and corrosion properties. Trends towards lower thickness combined with higher shape complexity of body panels are additionally leading to higher demands on formability of the sheet metal. Therefore, mechanical properties describing the formability such as Lankford coefficient or so-called r-value, strain hardening exponent, elongation, forming limit curves etc. are receiving more and more attention in sheet metal manufacturing as well as body panel production. The mechanical properties constitute also the basis for the numerical simulation of press parts.

To what extent numerical simulations can predict the actual behavior of the material during forming based on the formability indicators such as r-value is not the subject matter of the current paper, but they are considered important and therefore meeting the requirements of the automotive manufacturers by the sheet metal manufacturer is essential.

Background

Though there are no strong and conclusive evidences that suggest higher r-values lead to better formability, requirements of the current standards still must be met. Increasing r-values of 6016 alloys produced at Aluminium Duffel has been the motivation for a project aiming at understanding the effect of manufacturing process parameters on this indicator. As the hot rolling process of aluminium alloys is known to significantly affect the crystallographic texture [1], this study has been focused on investigating the effect of hot tandem rolling on the r-values of a specific 6016 alloy.

Manufacturing Process

Manufacturing process starts with casting of ingots either by Direct chill Casting (DC) or Electro-Magnetic Casting (EMC). In the current study, only DC was considered. After a homogenization and pre-heating, the ingot is hot rolled in a single stand reversing break-down mill to an intermediate gauge of about 20-40 mm and subsequently further hot rolled in a 3-stand tandem mill to the final hot rolled gauge of about 5-10 mm. The hot rolled material is coiled at an exit temperature of about 250-350 °C that is left for cooling in the air. After reaching the ambient temperature, the material is cold rolled to final gauge of about 1.0 to 1.50 mm. An intermediate annealing step may exist at an intermediate gauge between the hot rolled gauge and finish gauge. The final product is finally solution heat treated.

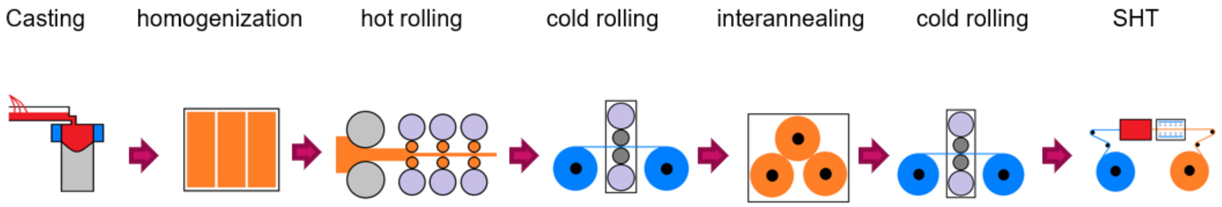

Figure 1. Schematic of manufacturing process

Final product is subjected to tensile testing according to ISO 6892-1 after allowing a certain number of days for natural aging. R-values are measured in rolling, transverse and 45° to rolling direction at a tensile strain of 8-12%. R-values hereafter in this report refer to those in the transverse direction.

Experiments and Modeling

The tandem mill was chosen for the study due to its simpler nature to model compared with a break-down mill. Also, relatively thin gauges in the tandem mill justify the assumption that temperature and strain rate across the thickness in the roll bite are uniform and therefore an average strain rate can be considered over the cross section. Average strain rate in the tandem mill was calculated from equation (1) which was derived by dividing the effective homogenous strain in plane strain by the duration of contact.

$$\dot{\varepsilon} = \frac{100\,V\,ln(t_{in}/t_{exit})}{3\sqrt{3D(t_{in}-t_{exit})/2}}\,. \qquad (1)$$

Where V is the linear speed at the exit of the last stand in m/min, D is the roll diameter in mm, t_{in} is the entry gauge to the tandem mill and t_{exit} is the exit gauge from the mill (both in mm). This is clearly a rough approximation as all stands are represented as one, but enough to take the most important parameters into account for the purpose of our investigation.

Temperature was measured continuously at the entry and exit of the mill that would allow calculation of instantaneous Zener-Hollomon parameter.

As temperature and strain rate play the most important role in recrystallization and texture development [2-5], several rolling experiments were conducted with the aim to cover a wide range of temperatures and strain rates with practical significance. The materials were processed to the end from which samples were taken for testing and analyses as the aim of the study was r-values of the finished product. Having an exact knowledge of hot rolling process parameters (entry and exit tandem temperatures and tandem speed) for the collected samples is essential for the modeling and analyzes purpose, therefore, location of samples on the end product were traced back to the tandem gauge to identify the entry and exit temperatures for the samples. Under standard rolling conditions where an exit temperature is targeted, speed varies a lot which makes the identification of relevant speed for the taken sample difficult. For this reason, tandem mill was operated at a constant speed for these experiments. Entry and exit temperatures to the tandem mill and exit speeds were recorded for further analyses and modeling. These experiments are graphically represented below.

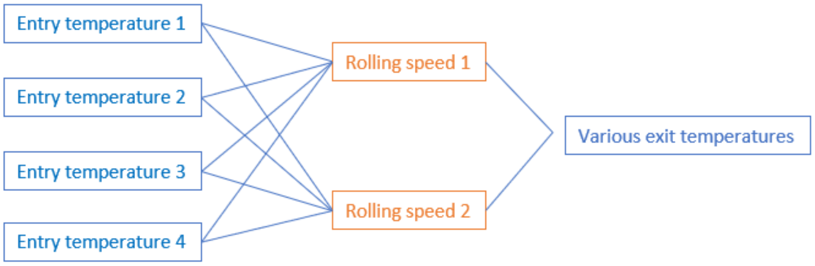

Figure 2. Graphical representation of first experiments at constant speed

Texture in aluminum alloys for the most part is developed during hot rolling and r-value of the final product is strongly dependent on the texture [6, 7]. Even though intensity of various texture components may change downstream in the process, fingerprint of hot rolled texture will still be dominant. Our strategy in this work was to relate the r-values of the final product to the hot rolling conditions in the tandem mill affecting recrystallization.

Various investigations in the past [2, 5, 8] have successfully modelled the recrystallization behavior of aluminum alloys after hot rolling. Time for 50% recrystallization is often modelled by equations of type

$$f = Z_{def}^{b} \cdot Z_{rex} \,. \tag{2}$$

Where Z_{def} is the well-known Zener-Hollomon parameter defined as

$$Z_{def} = \dot{\varepsilon}\, exp\left(\frac{Q_{def}}{R\,T_{in}}\right).$$

which may be considered as a measure of stored energy in the material during hot deformation and in which, Q_{def} is the activation energy for deformation and R is the universal gas constant. Z_{rex} describes the kinetics of recrystallization after hot deformation and is defined by

$$Z_{rex} = exp\left(\frac{Q_{rex}}{R\,T_{exit}}\right).$$

where Q_{rex} is the activation energy for recrystallization.

In the above expressions, T_{in} and T_{exit} are deformation temperature and holding temperature in K which correspond to entry temperature to tandem and coil temperature after tandem respectively.

For all experiments, f-values were calculated and r-values of those experiments were plotted against ln(f), good correlation was found as shown in Figure 3 below. Model constants (Qdef , Qrex and b) where taken from literature as the main interest lied in the trends rather than in absolute values.

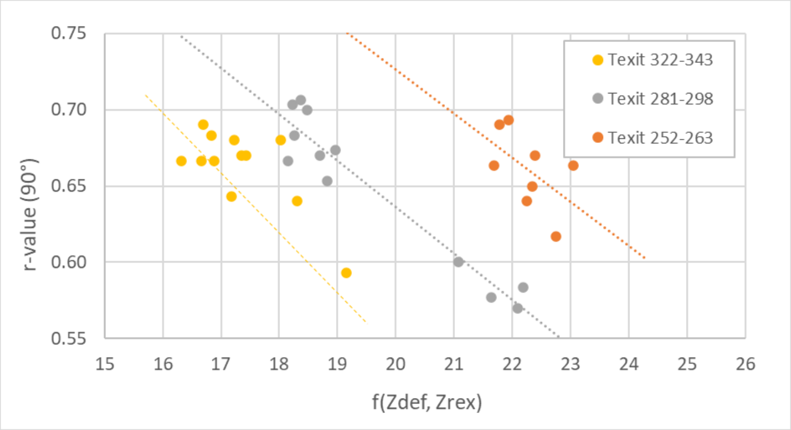

Figure 3. r-values correlate strongly with ln(f) in separate groups of holding temperature T_{exit}.

Since exit temperature from the mill was not a target, variations of it were inevitable and these variations seemed to negatively affect the fit between the measured r-values and values predicted by the model (Figure 3). To confirm this, a new set of experiments were designed and performed targeting specific exit temperatures following the scheme of Figure 4.

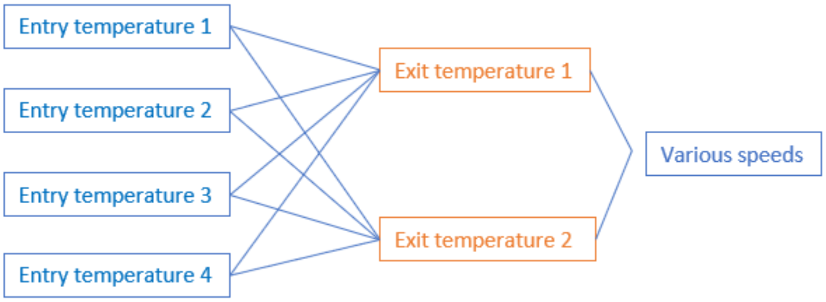

Figure 4. Scheme of second set of experiments targeting exit temperature

Results of these experiments are presented in Figure 5 below.

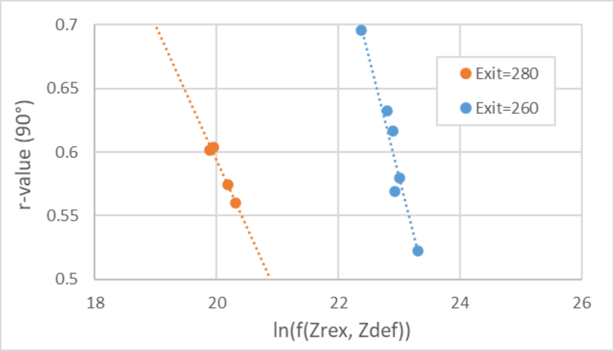

Figure 5. Reducing the variations in exit temperature improves the correlation between r-values and function f.

Thus, by suppressing variations in the exit temperature, the fit between r-values and ln(f) improved.

Even though equation (2) seems to be able to predict the r-value reasonably, but relative role of entry and exit temperatures on it is still not clear.

From the plots of Figure 1 , values of ln (f) at a given r-value, say 0.6, can be extracted for every T_{exit}. We call the values of function f at this given r-value, f_0 ,which is clearly a different value for every T_{exit}. By doing so, following table is obtained.

Table 1. Values of function ln(f) at r = 0.6 for different values of T_{exit}.

T_{exit}	263	281	284	294	322
$\ln(f_0)$	22.3	20.8	20.6	19.9	17.9

$\ln(f)$ can be written as:

$$\ln(f) = b\ln(Z_{def}) + \ln(Z_{rex}) = b\,ln(\dot{\varepsilon}) + \frac{b\,Q_{def}}{R\,\cdot T_{in}} + \frac{Q_{rex}}{R\cdot T_{exit}}.$$

At a fixed value of r, say 0.6, we rename f to f_0 and introduce a new parameter B:

$$B = \frac{ln(f_0)}{b} - \frac{Q_{rex}}{b\,R(T_{exit})} = \frac{ln(f_0) - \ln(Z_{rex})}{b}. \tag{3}$$

and we arrive at

$$\dot{\varepsilon} = exp\left\{B - \frac{Q_{def}}{R\cdot T_{in}}\right\}. \tag{4}$$

It can easily be seen that $B = \ln(Z_{def})$.
Now for each pair of T_{exit} and $\ln(f_0)$ in Table 1, parameter B can be calculated to obtain Table 2.

Table 2. Values of B calculated from equation(3) using values of Table 1.

T_{exit}	263	281	284	294	322
$\ln(f_0)$	22.3	20.8	20.6	19.9	17.9
B	50	50	50	50	50

As seen in Table 2, all combinations of T_{exit} and f_0 result in the same value of B indicating that exit temperature has had no effect on the r-value. It follows automatically from equation (4) that a constant Z_{def} value is enough to provide a constant r-value. Plot of Figure 5 confirms this statement.

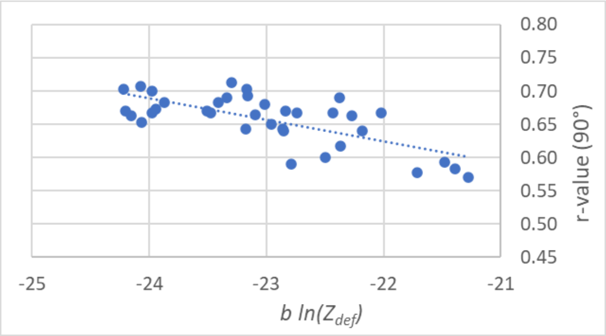

Figure 6. Good correlation between Zener-Hollomon parameter and the r-values independent from T_{exit}.

Holding temperatures or T_{exit} in this study have probably not been sufficiently high to trigger recrystallization and therefore Parameter B appears to be independent from it. To confirm this, a DSC test was done on a quenched hot band material after tandem mill to determine the recrystallization peak temperature. Results of this test is shown in Figure 7.

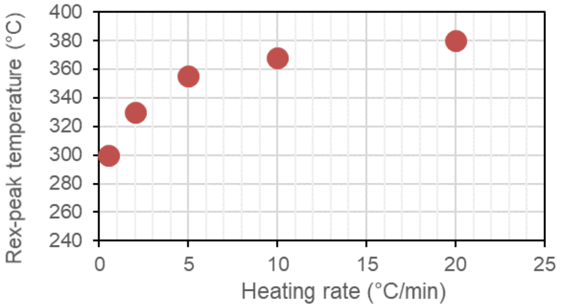

Figure 7. Recrystallization peak temperature determined by DSC test on one of the hot rolled materials of the study.

The highest heating rate is most relevant for this study as recrystallization of hot rolled material will start to take place with a minimum delay and loss of driving force.

Recrystallization peak temperatures in Figure 7 are much higher than holding temperatures in this study and therefore we conclude that no recrystallization has taken place immediately after hot rolling. Microstructure of the hot band material after coiling and cooling is shown in Figure 8.

Figure 8. Across thickness microstructure of naturally cooled hot band after tandem mill. No recrystallization has taken place

Practical Application

Based on what discussed, a minimum value of Zener-Hollomon parameter (Z_{def}) is required to reach a minimum desired r-value and having a (nearly) constant Z_{def} throughout the coil is necessary to obtain a (nearly) constant r-value throughout the coil. A constant Z_{def} implies a relationship between rolling speed and temperature as demonstrated in Figure 9.

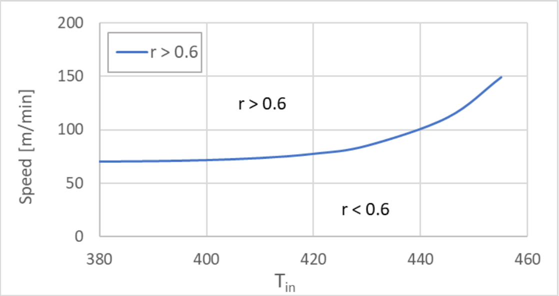

Figure 9. Desired relationship between tandem entry temperature and tandem speed to achieve a constant $\boldsymbol{Z_{def}}$. The curve represents a certain minimum r-value (axis scales are arbitrary here)

Thus, desired relationship between entry temperature and speed is in such way that increasing temperature requires an increase in speed and vice versa. All the speed-Temperature combinations above the curve in Figure 8 will consequently result in higher r-values than that represented by the curve (0.6 here) and combinations below the curve will result in lower r-values (assuming identical processing conditions downstream in the process).

Conclusions

Despite several operations between hot rolling and final product, there is a clear and visible connection between the tandem rolling process and r-value of final product. Entry temperature to the tandem mill and speed of rolling significantly affect the r-value of the final product. Lower temperatures and higher speeds increase the r-value (Figure 5, Figure 7). Exit temperature from the tandem mill seems not to influence the r-value (for the alloy studied here and within the temperature range of this study). Combined effect of entry temperature and rolling speed described by the Zener-Hollomon parameter can effectively be used to influence the r-value of the final product. This relationship between temperature and speed can be used to steer the rolling mill in such a way that not only a minimum r-value is safeguarded, but also variations of it along the length are minimized.

Acknowledgements

This work was part of an improvement project in Aluminium Duffel BV and the author is grateful for the support and permission to conduct all the necessary experiments and tests.

References

[1] Texture control by thermomechanical processing of AA6xxx Al-Mg-Si sheet alloys for automotive applications - a review. O. Engler, J. Hirsch. Materials science and engineering, A336, (2002) pp.249-262. https://doi.org/10.1016/S0921-5093(01)01968-2

[2] Modelling the Microstructural changes during hot tandem rolling of AA5xxx Aluminum alloys: Part I. Microstructural evolution. M.A. Wells et.al. Metallurgical and materials transactions, 29B (1998), pp. 611-620. https://doi.org/10.1007/s11663-998-0096-9

[3] Modelling the Microstructural changes during hot tandem rolling of AA5xxx Aluminum alloys: Part II. Textural evolution. M.A. Wells et.al. Metallurgical and materials transactions, 29B (1998), pp. 621-633. https://doi.org/10.1007/s11663-998-0097-8

[4] Modelling the Microstructural changes during hot tandem rolling of AA5xxx Aluminum alloys: Part III. Overall model development and validation. M.A. Wells et.al. Metallurgical and materials transactions, 29B (1998), pp. 709-719. https://doi.org/10.1007/s11663-998-0106-y

[5] Mathematical model of deformation and microstructural evolution during hot rolling of Aluminum alloy 5083. M.A. Wells et.al. Materials science and technology, **19** (2003), pp. 467-476. https://doi.org/10.1179/026708303225010713

[6] Recrystallization textures and plastic anisotropy in Al-Mg-Si sheet alloys. O. Engler, J. Hirsch. Materials Science Forum, 217-222 (1996), pp. 479-486. https://doi.org/10.4028/www.scientific.net/MSF.217-222.479