Proceedings of the 9th International Conference on Aluminium Alloys (2004) 1086
Edited by J.F. Nie, A.J. Morton and B.C. Muddle

Reduction of Temperature Extremes at the Die Exit in Aluminum Alloys Extrusion

D. S. Salonine, H.J. McQueen

Mechanical Engineering, Concordia University, Montreal, Canada, H3G1M8

Keywords: hard aluminum alloys, hot extrusion, billet preheating, die cooling

Abstract

In extrusion of billets with initially uniform temperature, the maximum temperature at the periphery varies with length of the emerging extrudate. The permitted maximum for an alloy is determined by the lower melting point at which surface cracking ruins the product. Even less extreme values cause problems by increasing the tendency to non-uniform recrystallization with loss of strength. A potential solution to the problem is gradient billet heating where the nose is hotter so that the reduced initial pressure and work gives a smaller rise in temperature. Another solution is direct die cooling to extract more of the heat generated in the hot zone and thus lower the temperature at the die land. The results of investigations clarify the extent that various measures can succeed.

1. Introduction

Hard aluminum alloys are used in a range of application in the automotive, aerospace and defence industries. For aluminum alloys, extrusion is a very effective metal forming process that transforms a billet into an elongated shape with a complex cross-section and easily finished surface. Wide and thorough reviews on extrusion have been made [1-4] with particular attention to aluminum [5-7]. The billet is softened by preheating slowly during passage through a tunnel furnace or quickly in an inductor prior to extrusion. The billet temperature T_B and the ram speed V_R are significant determining parameters of an extrusion process for which the alloy, the chamber diameter, the billet lengths, and the die configuration have been specified. The exit metal temperature T_M in the die opening determines both the maximum permissible metal flow speed V_M and the mechanical properties of the extrudate. The temperature rise is greater for higher extrusion ratios and ram speed; reduction in the latter to maintain surface quality decreases the productivity (and also the initial pressure). A reduction in surface exit temperature is produced by a greater decrement in billet temperature that raises the initial pressure and might require lowering the speed [3-6]. Any further increase in velocity results in thermal cracking because of melting of the eutectic at the grain boundaries of the cast billet.

The evolution of microstructure and the effect on properties have been summarized [2, 5, 9]. Upon extrusion, the hard aluminum alloys are usually solution treated. In this case, the few nuclei cause catastrophic grain growth (up to 3 - 5 mm) in the peripheral zones of the extrudate. Such a surface zone has poor mechanical properties (especially fatigue).

Because extrusion is not a continuous process like rolling or drawing, the temperature distribution is time dependent and the transient takes a sizable part of the extrusion cycle. As long as extrudate temperature is increasing, extrudate mechanical properties change too thus giving rise to variations along the length. The most common productivity improvements increase metal velocity in association with decreasing initial billet temperature T_B. But at the same time, the variation of the extrudate mechanical properties in the radial direction increases. That is why for hard aerospace alloys it is important to develop improvements that make the process more stable and the product properties more uniform. Two such directions are considered in this work.

2. Gradient Billet Preheating

In the beginning of the hot extrusion for hard aluminum alloys, specific pressure has a peak associated with the establishment of a steady-state temperature field in the deformation zone (DZ). Then the needed pressure falls rapidly by 10-20% for soft alloys and 30-40% for hard alloys. This drop depends on the billet temperature and metal velocity, being related to T_M - T_B. Furthermore, in direct extrusion, the needed pressure decreases progressively by 30-50% from reduction in friction due to shortening of the unextruded part of the billet. Simultaneously, the force applied must be decreased quickly by the same 10-40% and then gradually by 30-50% to restrict the metal velocity and corresponding metal temperature rise thus avoiding cracking. In consequence, unnecessarily powerful presses are used only to begin the process even in indirect extrusion. One solution is to use additional cylinders to start extrusion; this is costly. New problems appear with the alignment of the equipment. Moreover, the ram and the container remain unnecessarily loaded. A more attractive solution is to perform gradient billet preheating ("taper-heating") and then insert the billet in the container with the hot end next to the die [10-17]. Furthermore, velocity increase and more uniform properties of the extrudate in the longitudinal direction can be expected.

In choosing the temperature gradient, there are several different ideas of why and how much the back-end has to be colder. Furthermore, the results achieved are very diverse:

1) The colder back-end is heated during the extrusion cycle so that every part of the billet is at optimum temperature as it reaches the die [1]. - One may think that the remainder of the billet is heated by friction between the billet and the container using the work of the hydraulic press. To provide invariable input metal temperature for the DZ and to make the extrusion process steady-state, there is much more logical and cheaper solution - to hold the container temperature below the initial temperature of the billet. The optimum temperature difference can be easy calculated [8].
2) The colder back-end provides heat extraction and compensation for the heat generation in the DZ [3]. - It has been shown [8] that the heat energy generated in some cross-section of the DZ increases the temperature in the same section and travels through and out of the DZ without any considerable conduction. The heat exchange processes in the DZ in the longitudinal direction are quite adiabatic due to high metal velocity for all aluminum alloys and all press capacities used. The boundary between elastic billet and the DZ is not defined by heat flow but by equivalent stress attaining the hot yield stress.
3) Optimum gradient of 150-300°C along the whole billet provides more uniform microstructure and mechanical properties and increases metal velocity about 20% for 2024 alloy [13]; Additional preheating of the nose-end (~100 mm) of the billet (∅230 x 500 *mm) with the gradient ~120°C along the remainder of the billet increases*

productivity about 10-15% [15]. - Because of the fast heat exchange in the billet and between the billet and the container in the radial direction, billet metal soon attains container temperature, so that any temperature gradient in the longitudinal direction will be lost. A relatively small velocity increase of 10 - 20 % confirms this.

4) The temperature gradient has to be located within the length of the DZ to make the process steady-state from the beginning. This provides stable extrudate properties and increases metal velocity about 25-65% for hard aluminum alloys [16, 17]. - The value of the temperature gradient must be T_M - T_B. The idea of this proposal is to pre-establish in the future DZ a temperature distribution that is typical for the steady-state period of the extrusion process. Just the same heat would be added into the fore-end of the billet that otherwise will be generated during the transient period of extrusion. This "quasi-steady-state" process will not have a transient period nor the load-stroke curve an initial peak.

The most common practical methods of realizing the temperature gradient in an aluminum billet are: 1) using two cylindrical inductors (for uniform and for additional gradient heating), 2) using one inductor with different energy outputs in various coils, and 3) appropriate positioning of the billet relative to the inductor. In all these cases of induction preheating, the external layers of the billet will be heated higher and the radial gradient will be higher than the longitudinal one. A significant longitudinal gradient over the length of the DZ will not be achieved; this was another cause of failure in previous attempts to realize rapid extrusion with gradient billet preheating. We will consider the methods where the heat energy is supplied to the front face of the billet, for example from a plane multi-coil inductor. In this case, the inductor output power P_I [W] and heating time t_G [s] can be calculated [18] as

$$P_I = \Delta T\, k\, A / 0.7\, l \qquad (1) \qquad \text{and} \qquad t_G = 0.4\, l^2 / a \qquad (2)$$

where ΔT - temperature difference [°C], A - billet cross-section area [m^2], l - heating depth [m]. According to [16, 17], $\Delta T = T_M - T_B$ and l equals the billet radius.

Extrusion parameters and calculated t_G and P_I values for a 200°C gradient are presented in Table 1. In going from case 1 to case 6, press capacity increases over a wide range from 6 to 200 MN. The values of R_E, R_B, and L are increased too, but in such a proportion that leads to a little decrease in the values of pressure, extrusion ratio and relative billet length, which corresponds to usual extrusion practice. Metal velocity values are typical for 2024 alloy. To realize significant temperature gradient in the DZ, P_I values are quite big. But if we compare them with the extrusion power $P_E = F \cdot V_R$, we will see that $P_I \approx 1/2\, P_E$ (likewise the pressure for the deformation in the DZ takes ~1/2 of the total pressure). An alternative method to realize the temperature gradient is to heat the billet uniformly and then to cool the back-end [12]. It takes a lot of energy both for heating and cooling and is rational only for cooling from homogenization preheating [4].

The success of retaining the billet gradient preheat in the short length of an expected DZ depends strongly upon fast transport of the billet from the preheating unit into the press container and synchronization of extrusion and all auxiliary operations. In an aluminum alloy, any delay will result in the equalization of temperature along the billet due to high thermal conductivity. The transportation time has to be notably less than t_G. The extrusion time t, the time of uniform preheating t_H, and the time of gradient preheating t_G are compared in Table 1. Time t_H is minimum to insure temperature difference in radial direction not more than 30°C [4]. For low capacity presses, the gradient preheating time is notably less than the extrusion time. In this case, the billet can be gradient heated directly on the press axis or even in the open container. For high capacity presses, the uniform preheating time is much more than the extrusion time, thus several billets must be undergoing induction heating at the same time. The gradient preheating takes a big part of the extrusion time and thus has to be performed outside the press in parallel with another extrusion.

Table 1: Time and power of gradient preheating for different capacity presses.

Case	Press capacity F (MN)	Extrus. radius R_E (m)	Billet radius R_B (m)	Billet length L (m)	Metal velocity V_M (m/min)	Extrus. ratio R n.d.	Extrus. time t (min)	Uniform heating t_H (min)	Grad. heating t_G (min)	Inductor power P_I (KW)	Extrus. power P_E (KW)
1	6	0,007	0,044	0,300	5,4	39,5	2,2	1,9	0,2	8,8	13,7
2	10	0,010	0,060	0,390	4,0	36,0	3,5	3,6	0,3	12,0	18,5
3	20	0,016	0,088	0,540	3,0	29,9	5,4	7,7	0,6	17,5	33,4
4	50	0,030	0,150	0,840	2,0	25,0	10,5	22,5	1,9	30,0	66,7
5	100	0,050	0,230	1,200	1,6	21,2	15,9	52,9	4,4	46,0	126,0
6	200	0,080	0,340	1,630	1,2	18,1	24,5	115,6	9,6	68,0	221,5

3. Experiments

The experiments were undertaken in the tube shop of Samara Metallurgical Plant (Russia) in 1986. The tubes of several aluminum alloys have been extruded from billets continuously cast with a central hole (∅165 x ∅63 x 690 mm) on a indirect press 15 MN with moving lubricated mandrel. Gradient billet preheating was simulated in two ways: 1) by placing a hotter disk of the same alloy between the billet and the die and 2) by using a dummy block (with the die-insert) hotter than the billet - see Table 2. The disks or the dummy block were heated before every extrusion cycle in a special inductor.

Table 2: Modeling of gradient billet preheating.

Alloy	Tube dimensions	Uniform heating		Grad. billet pre-heating				Velocity increase
		T_B	V_R	T_B	T_{DISK}	T_{DUMMY}	V_R	
2017	∅38 x 6	260	1.6	180		430	2.0	+25%
5083	∅53 x 5	320	1.2	270		440	2.0	+67%
2024	∅38 x 5	270	0.8	240		400	1.0	+25%
5083	∅57 x 4	260	1.6	180	500		2.0	+25%
2024	∅53 x 4	280	1.2	200	510		1.6	+33%
7075	∅58x12.5	310	1.2	120	470		2.0	+67%

For T_B and T_{DISK} combinations shown in the table, no pressure peaks were observed. For hotter and thicker discs, the pressure was somewhat lower in the beginning of extrusion. In extrusion with a hot dummy block, a small pressure peak was observed because we could not use dummy blocks as hot as the discs. Aluminum disks are extruded and come out through the die. Unlike the discs, the dummy blocks stay in the press and also have to extract the friction heat from the DZ as usual. Velocity increases of 25 to 67% were obtained in both cases. We consider both these gradient pre-heating cases only as simulations. Hot discs can not be used in extrusion practice because of surface defects due to not quite perfect welding between the disc and the billet. Hot dummy blocks do not allow realization of all the processing advantages as was explained. For real extrusion, flat inductors must be developed and mounted close to the container of the extrusion press.

4. Die Zone Cooling

The heat sources acting during the deformation can be divided into two different categories: volumetric and surface. In extrusion, the volumetric sources exist in the DZ. The volumetric sources heat the extrudate almost uniformly across the entire radius and their action can be balanced by using an appropriate longitudinal temperature gradient that was discussed above. The surface sources appear between the moving metal and the "dead" zone and their magnitudes are

$$q_S = \tau \cdot v \ \ [W/m^2], \qquad (3)$$

where τ is the shear stress. The surface sources cause non-uniform heating of the extrudate in the radial direction. This can not be balanced by any sophisticated billet preheating before extrusion and this energy must be continually removed during extrusion; the energy generated due to friction between the billet and the container is lost to the cool container. That is why the process improvements that involve the cooling of the die zone are attractive [19-24]. The die [19-21] or the container liner [22] can be cooled. Increases in velocity from 20% [21] to 100% [20] are claimed. The most suitable plan is to remove all the heat energy generated by friction between the moving metal and the "dead" zones as proposed in [23]. Heat flow going out into the die is

$$q_D = \Delta T \ k / \delta \ , \qquad (4)$$

where δ - equivalent die thickness [m], ΔT - temperature difference between die face and cooling channel surface [°C]. From equality of the generated (3) and outgoing (4) heat flows:

$$\delta = 2 \ \Delta T \ k / \sigma_S \ V_M \qquad (5)$$

Equation (5) shows that the higher the flow stress and metal velocity are, the closer the cooling surface has to be to the die face. So, cooling of the end of the container liner can not give a significant improvement. The calculated δ values for ΔT = 400 °C for the same extrusion examples as in Table 1 are shown in Table 3. It is seen that, for all press capacities, the δ values are almost equal to die land widths. Thus, the cooling channels have to be positioned right next to the die land [24].

Table 3: Optimum die cooling.

Case	Press capacity ***F*** (MN)	Extrusion diameter ***d*** (mm)	Billet diameter ***D*** (mm)	Metal velocity V_M (m/min)	Equivalent thickness δ (mm)
1	6	14	88	5,4	10
2	10	20	120	4,0	14
3	20	32	175	3,0	19
4	50	60	300	2,0	28
5	100	100	460	1,6	35
6	200	160	680	1,2	47

To predict possible metal velocity increase from die cooling in combination with gradient billet preheating, the same calculation approach can be used as in [8]. In Table 4, extrusion with: 1) high gradient (in the future DZ) billet preheating, 2) intensive die cooling (δ = R_E = 16 mm), 3) both gradient preheating and die cooling are compared with the "base" extrusion process from Table 1 (case 3). It is seen that metal velocity V_M can be increased: 3.4 → 4.6 → 5.3 → 6.0 m/min. If the speed is not the primary goal, we can decrease the difference between the surface and axis temperatures of the product ΔT_S - see the last three rows in Table 4.: 85 → 56 → 21 °C.

Table 4: Extrusion with gradient billet preheating and die cooling.

Case	Metal velocity V_M (m/min)	Billet temperature T_B (°C)	Temperature difference ΔT_S (°C)	Surface temperature T_S (°C)
Base process	3,4	345	76	499
Gradient Heating	4,6	303	89	499
Die Cooling	5,3	355	65	498
GH+DC	6,0	310	85	501
GH+DC	5,0	305	56	467
GH+DC	4,0	300	21	427

5. Conclusions

The most common improvement directions in extrusion are increased metal velocity (productivity) along with decreased initial billet temperature. It is important to develop the improvements, which make the process more stable and the product properties more uniform. The action of the volumetric heat sources can be balanced by using an appropriate longitudinal temperature gradient. The value of the gradient must equal T_M - T_B and it must be located in the DZ. The energy generated due to the surface heat source at the dead metal zone must be removed by die zone cooling.

References

1. R. Chadwick, Metal. Rev., 4, 1959, pp. 189-255.
2. T. Sheppard, S.J. Paterson, and M.G. Tutcher, On the Development of Structure during the Extrusion Process, Microstructural Control in Al Alloys, 1986, pp. 123 - 154.
3. I. L. Perlin, L.H. Raitbarg, Metals Extrusion Theory, M., "Metallurgia", 1975.
4. L.H. Raitbarg, Extrusion Production. M., "Metallurgia", 1984.
5. H.J. McQueen and O.C. Celliers, Application of Hot Workability Studies to Extrusion Processing, Can. Metal. Quart, 35, 1996, pp. 305-319 and 36, 1997, pp. 73-86.
6. V.N. Scherba, Aluminum Alloys Extrusion, "INTERMET ENGINERING", 2001.
7. H.J. McQueen, D.S. Salonin, and E.V. Konopleva, Extrusion Design and Modeling of Al Alloys, Multidisciplinary Design in Engineering, CSME-MDE, Montreal, 2001.
8. D. Salonine and H. McQueen, Analysis of Extrusion Conditions for Hard Aluminum Alloys, Enabling Technologies for Light Metals and Composite Materials, Met. Soc. CIM, Montreal, 2002, pp. 931-947.
9. Yu.M. Vainblat Aluminum alloys microstructure diagrams and maps, Metals, 2, 1982, pp. 82-87.
10. B.I.O.S. Final Report, London (H.M. Stationery Office), 1656, 1948.
11. E.K.L. Haffiner and R.M.L. Elkan, Met. Rev., 2, 1957, p. 263.
12. Engineer, 204, 1957, p. 579.
13. L.H. Raitbarg and oth., Progressive Technology of Shapes and Tubes Production, 1969, pp. 36-46.
14. T.N. Golohmatova and oth., Light Metal Technology, 1, 1971, pp.16-18.
15. A.V. Gusev and oth., Metal forming Theory and Technology, M., "Metallurgia", 1982, pp. 45-51.
16. D.S. Salonin, Shapes Extrusion Method, USSR Patent 1 223 489, 1985.
17. D.S. Salonin and V.V. Rudnev, Metals Extrusion Method, USSR Patent 1 422 488, 1988.
18. A.I. Pekhovitch, V.M. Gidkikh, Heat Calculations for Solid Bodies, 1976.
19. A. von Zeerleder, Technology of Light Metals, New York, London, 1949.
20. T.F. McCormick, Trans. ASME, 75, 1953, p. 1525.
21. A.I. Baturin, Pressing Production, 8, 1966, pp. 5-9.
22. M.F. Golovinov, Trans. III Conference on Metals Extrusion, 3, 1968, pp. 88-100.
23. D.S. Salonin, Extrusion Method, USSR Patent 1 293 902, 1986.
24. D.S. Salonin, L.E. Filatova, Air-cooling Tools for Tube Extrusion, Light Metal Technology, 8, 1988, p.76.