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Extrusion of aluminum tubes with axially graded wall thickness and mechanical characterization

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Abstract

In this study the indirect extrusion of seamless aluminum tubes with variable wall thickness was investigated. Therefore, an axially moveable stepped mandrel was applied. Investigations revealed that wall thickness transitions can either be graded over the tube length or very sharp. The microstructures in thin-walled and thick-walled tube sections were investigated. The local variation of the extrusion ratio and with that the tube wall thickness, product velocity and product temperature during the process lead to significantly different local microstructures at T_B=400°C. At T_B=500°C the microstructure was homogeneously recrystallized with similar grain size in all different tube sections. Furthermore, the mechanical tube properties were characterized by three point bending tests.

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Keywords: Extrusion, variable wall thickness, tailored tubes, aluminum, microstructure, three point bending test

1. Introduction

Modern lightweight constructions more and more demand for customized solutions in order to meet customers’ requirements of increasing complexity [1]. Therefore, in the recent history approaches towards a flexibilization of extrusion processes and its products were investigated.

The manufacturing of bend profiles during hot metal extrusion can avoid post extrusion bending. On the one hand in [2] three-dimensional bend profiles were extruded by regulating the material flow in the die. On the other hand a guiding device behind the extrusion press was applied to create in-line three-dimensional bend extrusions [3].

Since the distribution of loads usually is not constant over the profile’s length, the development of extruded profiles with locally adapted cross sections would be desirable. Jäger et al. [4] showed the feasibility of local cross section reductions of hollow profiles by applying in-line electromagnetic compression subsequent to extrusion.

Further, it would be attractive for innovative lightweight constructions to adapt the wall thickness of extruded hollow profiles according to the actual load. For this reason laboratory-scale extrusion trials using an axially movable conic mandrel and lead as billet material were used in order to show the feasibility of wall thickness variations by changing the inner tube diameter during extrusion [5]. Negendank et al. [6] used a stepped mandrel and a small industrial size 8MN extrusion press to show the feasibility of producing multiple wall thickness variations along tube direction for AA6060. Another possibility of changing the wall thickness of extruded hollow profiles is to vary the outer diameter by using movable die bearings [7]. In [8] both approaches (moving mandrel as well as movable die segments) were combined and hollow profiles with variable inner and outer tube diameter were extruded.

Aim of the current study was to extrude AA6060 tubes with axially variable cross sections and to analyze the product geometry as well as the local microstructure

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in different tube areas. Furthermore, the mechanical properties of tube sections with different wall thickness should be investigated by three point bending tests.

2. Experimental Procedure

2.1. Extrusion of seamless aluminum tubes with variable wall thickness

For the extrusion experiments conducted in this study the indirect extrusion process was used. The diameters of the die and the container were D_{die}=41mm and D_C=125mm. A thermocouple in the die bearing was applied to measure the profile temperature. The die was fixed on the hollow stem and therefore was heated indirectly by the container's heat prior to the trials. The variation of the wall thickness (t) of seamless aluminum tubes during the extrusion process was achieved by an axially moveable stepped mandrel (Fig. 1). The mandrel featured a tip diameter of 32mm with a shaft diameter of 37mm. Such as the die, the mandrel was also heated indirectly by the container's heat. Thus, the temperatures of die and mandrel were 50-100°C lower than the set container temperature and the billet temperature T_B. In order to change the tube cross section the mandrel was first moved in extrusion direction. This procedure is based on the well-known process of extrusion with moving mandrel. Once the mandrel step arrives in the die, the wall thickness will decrease. In order to manufacture multiple wall thickness transitions along the tube's length, the mandrel needs to be drawn back. Since the control system of the extrusion press did not allow mandrel motion against extrusion direction (ED) during the extrusion process, it was necessary to interrupt the extrusion before drawing the mandrel back to its starting position. Two variations of the draw back process were investigated. For the first the mandrel was simply drawn back using the billet piercing system of the press. The second alternative included the release of the pressure from the billet and subsequent repositioning of the mandrel to its starting position. Afterwards the extrusion was continued with extruding a thick-walled section again. The principle of the process is displayed in Fig. 1.

For the experiments homogenized, predrilled billets of AA6060 were used and heated to billet temperature T_B in an induction furnace. By using the described procedure two different extrusion trials were carried out and the wall thickness was changed multiple times during each extrusion. The ram velocity v_{ram} was set to 0.9mm/s. Both tubes were water quenched at the end of the hollow stem about 0.9m behind the die in order to 'freeze' the as extruded state and compare it to the T6 heat-treated state in future investigations. Table 1 presents the significant process parameters for the extrusion trials. Therein D_M describes the diameter of mandrel tip and mandrel shaft and R is the local extrusion ratio.

The microstructures of tube sections with constant wall thickness were analyzed after anodizing with barker's reagent. The mean grain size was then determined by linear intercepts of grain boundaries.

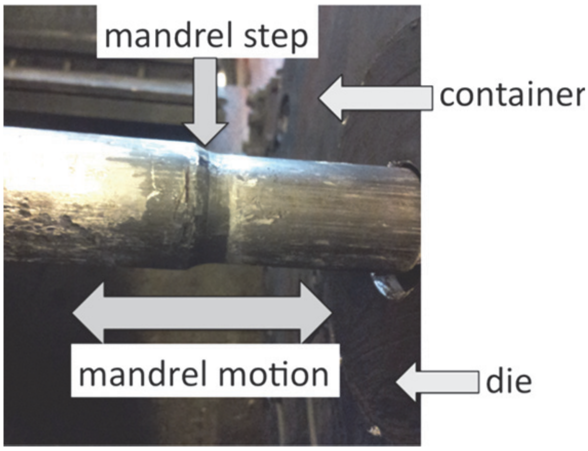

Fig. 1. Principle of extrusion of tubes with variable wall thicknesses using an axially moving stepped mandrel (ED⇒)

Table 1. Parameters of extrusion trials

No.	T_B [°C]	D_M [mm]	t [mm]	R	v_{ram} [mm/s]
1	500	32	4.5	22:1	0.9
		37	2.0	46:1	
2	400	32	4.5	22:1	0.9
		37	2.0	46:1	

2.2. 3-point bending tests

The mechanical properties of the extruded tubes were characterized by 3-point bending tests of tube sections. Aim was to investigate the influence of the local wall thickness (local degree of deformation) and the microstructure on the bending strength of the extruded tubes. These tests were performed on a 20t tension/compression machine using a bending mandrel. The diameter of the round bending mandrel tip was 20mm. Fig. 2 shows the experimental setup.

Thin-walled (t=2.0mm) and thick-walled (t=4.5mm) sections of each hollow profile with length of 250mm were tested. The distance between the supporting rolls was set to 100mm and the testing speed to 20mm/min. During the tests the force and the displacement of the machine's traverse was measured. With the maximal test force (F_{max}) the maximal bending moment $M_{b,max}$ was calculated using equation 1 [9], where L is the distance between the supporting rolls.

$$M_{b,max} = \frac{F_{max} \cdot L}{4} \quad \text{(eq. 1)}$$

For round tubes the area moment of inertia (I_y) is given in eq. 2 [10] by:

$$I_y = \frac{\pi}{64}\left(D_o^4 - D_i^4\right) \quad \text{(eq. 2)}$$

D_o and D_i describe the outer and inner tube diameter.

With eq. 1 and eq. 2 the bending stress σ_b can be calculated in dependence of the distance z from the neutral fiber with eq. 3 [9]:

$$\sigma_b(z) = \frac{M_{b,max}}{I_y} \cdot z \quad \text{(eq. 3)}$$

σ_b will be maximal at the tube surface (edge stress), where z is half of the outer tube diameter.

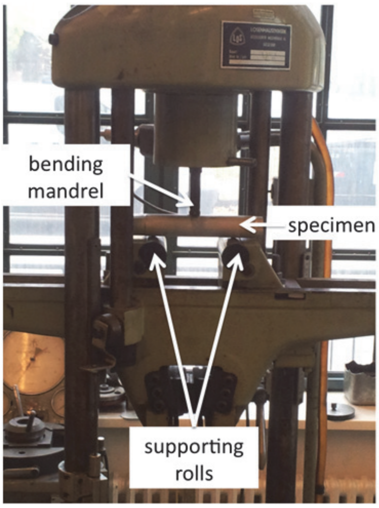

Fig. 2. Experimental setup for 3-point bending tests of tubes

3. Results and discussion

3.1. Extrusion of seamless aluminum tubes with variable wall thickness

Fig. 3 presents an example of a force-ram-displacement diagram gained during the experiments. In contrast to conventional indirect extrusion there is no steady state. Instead, multiple peaks of the overall force (F_{ov}) and the ram velocity (v_{ram}) can be noticed. This can be explained as follows. At the beginning of each wall thickness variation cycle the mandrel is positioned with its smaller cross section in the die orifice. Thus, when the force increases and reaches the flow stress of the material at the given conditions, the material starts to flow and a thick-walled tube section will be extruded. When the mandrel step reaches in front of the die, the gap between die and mandrel surface reduces. Subsequently, the wall thickness decreases and the extrusion ratio increases. This increase leads to higher necessary extrusion forces, thus F_{ov} increases. But contrary to the expectation of a more or less linear increase, a sudden decrease in F_{ov} accompanied with an abrupt acceleration of v_{ram} was observed before increasing.

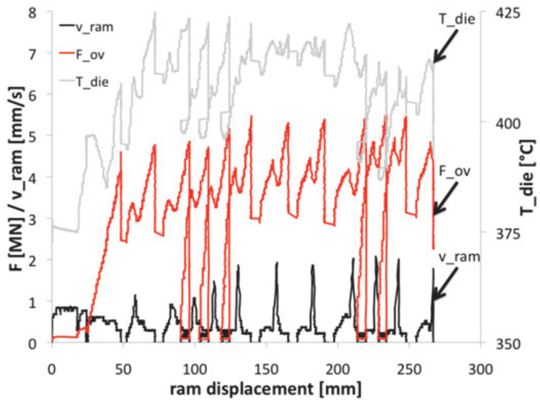

Fig. 3. Extrusion diagram showing multiple cycles of wall thickness variations for T_B=400°C

There are two possibilities that could explain this phenomenon. As previously found by finite element analysis (FEA) [6, 11], due to the inwardly directed material flow and lack of resistance by the moving mandrel, the outer tube surface loses contact to the die bearing and also to the mandrel tip as well as to the mandrel step when the wall thickness is varied. That means a reduction of the friction area and thus lower necessary F_{ov}. The second possibility is the backpressure acting on the area of the mandrel step. The material in the deformation zone in front of the die creates this pressure. As the distance between mandrel step and die decreases the pressure in that area increases resulting in higher extrusion force requirements. Once the mandrel step has entered into the die and the backpressure is overcome, the extrusion force decreases abruptly as can be seen in Fig. 3. At the same time v_{ram} increases significantly leading to the peaks in the v_{ram} curve. Afterwards v_{ram} remains about constant and F_{ov} increases due to the higher extrusion ratio, since the wall thickness now is reduced from 4.5mm to 2.0mm. When the mandrel shaft has entered about 15mm into the die the extrusion process was interrupted in order to draw the mandrel back to its initial position. The shear drops of the F_{ov}-curves in Fig. 3 represent these positions. The different procedures of mandrel drawback can also be distinguished in the force-ram displacement diagram. When the pressure on the billet is relieved before the mandrel is drawn back, the ram position changes about some centimeters against extrusion direction. This was not observed when the billet remained under pressure. After the mandrel was drawn back, the extrusion was continued with another cycle of wall thickness variation, starting by extruding a thick-walled tube section. The development of the temperature measured in the die bearing qualitatively follows the trend of F_{ov}.

3.2. Characterization of tube dimensions in transition zones between two wall thicknesses

Subsequent to the extrusion experiments the tubes were examined. A longitudinal section of transition areas in Fig. 4 proofs that the tube wall thickness was successfully changed during extrusion.

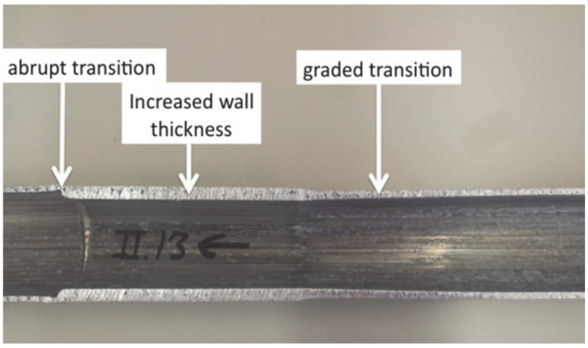

Fig. 4. Longitudinal section of tube with variable wall thickness showing abrupt and graded transition, (ED ⇐)

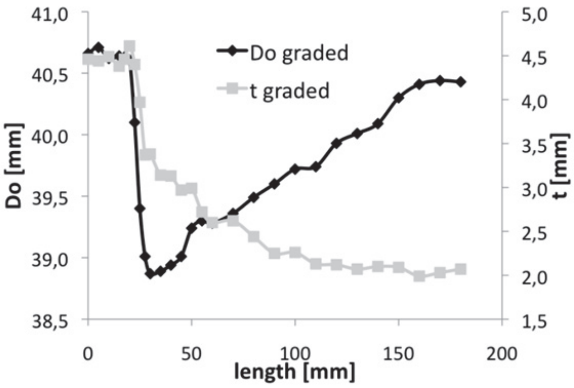

Fig. 5. Development of outer tube diameter Do and wall thickness t in graded wall thickness transition, ED ⇐

Caused by the process three different kinds of wall thickness transitions were observed. The first type is called continuous or graded transition since the wall thickness is varied continuously over a relatively long profile length (right side in Fig 4). This transition is generated when the mandrel step enters into the die. Since the gap between mandrel step and die reduces gradually with mandrel displacement, the tube wall thickness is also gradually decreased. The wall thickness development over the transition length is displayed in Fig. 5. It can be learned that the reduction of the wall thickness from t=4.5mm to 2.0mm takes place over a profile length of about 150mm. At the beginning the decrease is relatively sharp but then becomes gradually.

On the other hand when the extrusion is interrupted and the mandrel drawn back before resuming the extrusion, the wall thickness changes abruptly over a very short tube length. On the left side Fig. 4 shows that a wall thickness transition from t=2.0mm to t=4.5mm was achieved within a profile length of 1mm when the billet pressure is released before drawing the mandrel back to its starting position. When the pressure is not released before the drawback the result can be abrupt wall thickness transitions that are stretched in extrusion direction. Fig. 6 shows that in this case the wall thickness transition takes places over an extended tube length of 30mm. This can be explained by the reducing extrusion ratio when the mandrel shaft is pulled out of the die. When R is reduced, the remaining billet pressure can still be sufficiently high enough to force the material to flow through the now increased orifice between die and mandrel.

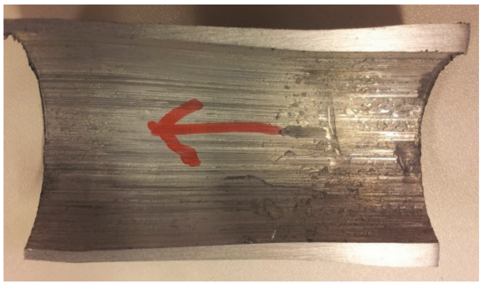

Fig. 6. Longitudinal section of stretched abrupt transition manufactured without releasing pressure from billet for mandrel drawback, (ED ⇐)

Thus, with abrupt wall thickness transitions tubes can be strengthened (‘tailored’) with increased cross sections in very localized profile areas that are highly stressed.

Furthermore, it was revealed that in the wall thickness transitions the tubes’ surfaces were dent. In order to give a quantitative evaluation of these observations, the development of the outer tube diameter was also determined in Fig. 5 for the continuous transition and for the abrupt transition (with relieved billet pressure) in Fig. 7.

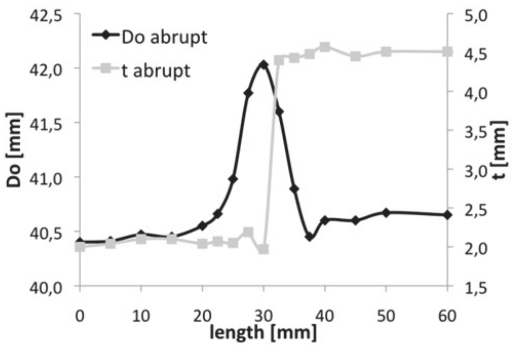

Fig. 7. Development of outer tube diameter Do and wall thickness t in abrupt wall thickness transition with released billet pressure, ED ⇐

As previously found [11], the reduced outer tube diameter in the graded transitions forms due to the lack of mandrel resistance against the inwardly directed material flow when the mandrel step is right in front of the die as well as in the die bearing. On the other hand in abrupt transitions manufactured without releasing the billet pressure a surface dent also developed (Fig. 6). In this case the material does not flow parallel to the extrusion direction after mandrel draw back but in direction of the mandrel surface. Thus, the previously extruded thin-walled section in contact with the die bearing is ripped off the bearing and a surface dent is formed [11]. Abrupt transitions formed after releasing the billet pressure for mandrel drawback have not yet been investigated by FEA. But the reason for the locally increased outer tube diameter (Fig. 7) should also be attributed to the material flow. As the material starts flowing inwardly in direction of the mandrel after the extrusion is resumed subsequent to the mandrel's draw back, it could have been deflected by the mandrel surface and directed towards the tube surface, resulting in the increased outer diameter. This effect will be further investigated in future work by FEA and detailed analysis of the microstructure in these regions.

3.3. Analysis of tube microstructures

The analysis of the tube microstructures revealed two significantly different types. Firstly, fully recrystallized microstructure consisting of relatively big, equiaxed grains was found at the higher billet temperature of T_B=500°C in all tube cross sections of t=2.0mm, t=4.5mm, the graded transition as well as the abrupt transition. Fig. 8 gives a characteristic example of this kind of microstructure. Fully recrystallized grains were also found at the lower T_B=400°C, when the extrusion ratio and thus the profile velocity as well as the local profile temperature were high, thus improving the conditions for recrystallization [12].

The mean grain sizes of the tube sections of constant wall thicknesses (t=4.5mm and t=2.0mm) are given in table 2. It can be learned that the microstructure and the grain size in these specific sections are very similar for TB=500°C. Thus, the differences in local degree of deformation, product velocity as well as the product temperature do not have an influence on the local microstructures in these specific areas. A comparison of the grain size of the thin walled areas between both tubes revealed a lower grain size for TB=400°C. Due to the lower TB the energy for grain growth during recrystallization is lower resulting in smaller grain size.

On the other hand when the extrusion ratio and the product velocity are low as they are during extrusion of the thick-walled section at TB=400°C, the microstructure is dominated by thin grains, which are elongated in extrusion direction (Fig. 9). Obviously these extrusion conditions did not generate sufficient energy for the activation of recrystallization processes. With higher magnification it was found that the grain boundaries are serrated. These serrations develop during the deformation and are an indication of dynamic recovery processes [13]. Because of the morphology of the elongated grains (very thin and long) a grain size determination could not be given.

Table 2. Grain size [μm] in dependence of local tube wall thickness t and T_B

t [mm]	T_B=500°C	T_B=400°C
2.0	132	81
4.5	126	deformed

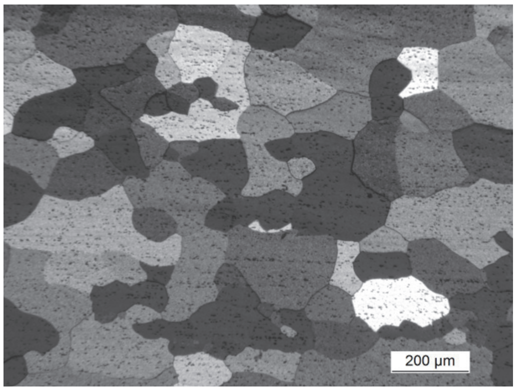

Fig. 8. Fully recrystallized microstructure with equiaxed grains T_B=500°C, t=2.0mm), ED ⇐

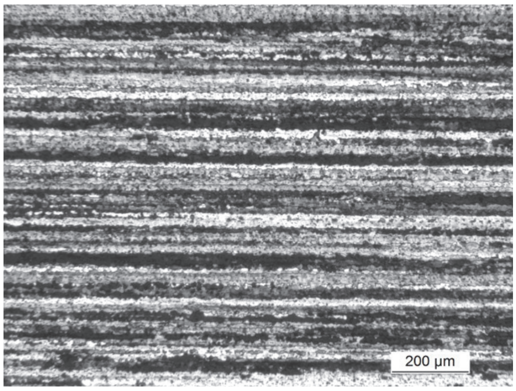

Fig. 9. Microstructure with grains elongated in ED (T_B=400°C, t=4.5mm), ED ⇐

3.4. Mechanical tube properties in 3-point bending tests

During the three point bending tests force-displacement curves were gained. From these curves the maximal forces were used in order to calculate the maximal bending moments (eq. 1) and the edge stresses (eq. 3) on the tube surface. The results are given in table 3.

When the calculated edge stresses are compared, it can be learned that for t=2.0mm as well as for t=4.5mm higher stresses were found for the tube extruded at the higher billet temperature of T_B=500°C. This observation can be explained by the higher solubility of especially Mg- and Si-atoms in the aluminum solid solution at the higher T_B. Since the tubes were water quenched behind the hollow stem, precipitation could be reduced leading to higher strength of the aluminum solid solution. This behavior was previously observed for the results of Vickers hardness measurements in [14].

Table 3. Results of three point bending tests

T_B [°C]	t [mm]	F_{max} [kN]	$M_{b,\,max}$ [Nm]	I_y [mm^4]	σ_b [MPa]
500	2.0	4.8	120	44766	54
500	4.5	19.3	483	84429	116
400	2.0	3.5	88	45625	39
400	4.5	15.2	380	84082	92

4. Conclusions

1. The wall thickness of aluminum tubes (AA6060) was successfully varied multiple times along tube direction during extrusion by applying axially moving a stepped mandrel.
2. Two significantly different wall thickness transition types were produced. The transition can either be manufactured gradually when the mandrel step is continuously moved into the die. Or the transition can be very sharp (abrupt) when the extrusion is stopped for drawing the mandrel back to its starting position. Thus, load adapted (tailored) aluminum tubes with thick-walled sections located only in highly stressed areas can be manufactured. Since less stressed profile areas can be produced with lower wall thicknesses, the overall profile weight can be reduced.
3. The outer tube diameter in wall thickness transitions differed from the set values. This is due to the inwardly directed material flow and lack of resistance by the mandrel during the transitions [11].
4. The variation of the local extrusion ratio and thus the product velocity as well as the product temperature during the experiments lead to significantly different microstructures in thin-walled and thick-walled sections of the tube extruded at T_B=400°C. At T_B=500°C the microstructure consisted of recrystallized grains with similar grain size in all parts of the tube.
5. Results of three point bending tests revealed that sections of a tube extruded at T_B=500°C showed higher strength than sections with same wall thicknesses extruded at T_B=400°C. This was explained by solid solution hardening.

Acknowledgements

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References

[1] Otto Fuchs KG Meinerzhagen, Tailored aluminium tubes – extruded tubes with variable wall thickness, International Aluminium Journal Vol. 89, 10, 2013, pp. 35-36
[2] K. B. Müller: Bending of extruded profiles during extrusion process, International Journal of Machine Tools and Manufacture, Vol. 46, 2006, pp. 1238-1242
[3] S. Chatti, M. Hermes, M. Kleiner, Three-Dimensional Bending of Profiles by Stress Superposition Advanced Methods in Material Forming, 2007, pp. 101-118
[4] A. Jäger, D. Risch, A.E. Tekkaya, Thermo-mechanical processing of aluminum profiles by integrated electromagnetic compression subsequent to hot extrusion, Journal of Materials Processing Technology, Vol. 211, 2011, pp. 936-943
[5] T. Makiyama, M. Murata, Materials Science Forum, Vols. 396-402, (2002), pp. 513-520
[6] M. Negendank, S. Müller, W. Reimers, Extrusion of tailored alumimun tubes, Proceedings of the 8th World Congress Aluminium Two Thousand, 14.-18.5.2013, Milan, Italy, ISBN 978-88-87971-0-2
[7] Selvaggio, A., Chatti, S., Ben Khalifa, N., Tekkaya, A. E., New developments in extrusion of profiles with variable curvatures and cross-sections. In: Proceedings of the Tenth International Aluminium Extrusion Technology Seminar ET´12, Miami, Florida (USA), 2012, pp. 505-512
[8] K. Hara, N.Ohtake, K. Horita, Variable-Shape Extrusion of Aluminum Square Pipes using DLC coated dies, New Diamond and Frontier Carbon Technology, Vol. 14, 2004, pp. 331-34004
[9] B. Heine, Werkstoffprüfung Ermittlung von Werkstoffeigen-schaften, 2003, Carl Hanser Verlag, München Wien, ISBN 3-446-22284-7
[10] K.-H. Grote, J. Feldhusen, Dubbel Taschenbuch für den Maschinenbau, 22. Auflage, 2007, Springer, Berlin, Heidelberg, New York, ISBN 978-3-540-49714-1
[11] M. Negendank, S. Müller, W. Reimers, Finite element analysis of material flow and characterization of tube dimensions of indirectly extruded tailored aluminum tubes, Proceedings of THERMEC 2013, Las Vegas, Nevada, USA, accepted manuscript
[12] E. D. Sweet, S. K. Caraher, N. V. Danilova, Xinquan Zhang, Effects of Extrusion Parameters on Coarse Grain Surface Layer in 6xxx Series Extrusions, In: Proceedings of the Eighth International Aluminum Extrusion Technology Seminar, Vol. I, 2004, pp. 115-126
[13] J.F. Humphreys, M. Hatherly, Recrystallization and Related Annealing Phenomena, second edition, 2004, Elsevier
[14] M. Negendank, S. Müller, W. Reimers, Microstructural development and mechanical properties of indirectly extruded tailored aluminum tubes, International Congress on Light Materials –Science and Technology (LightMAT2013), 2013, Bremen, Germany, http://www.dgm.de/tagungen/?tgnr=1171&cat=&edate=05.09.2013&lg=en