Formability of recycled aluminium : advantages of a rapid solidification process

Formability of Recycled Aluminium – Advantages of a Rapid Solidification Process

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Processing by rapid solidification is a promising new technique for the recycling of aluminium scrap. This method includes rapid solidification (melt spinning), followed by consolidation (direct hot extrusion). The material obtained is semi-finished and it has to be processed further into final products. The semi-finished material can be shaped by forming.

After introducing this new recycling technique, the influence of processing parameters on the material's plastic properties is discussed. The formability of this particular material is evaluated as a function of the forming temperature and examples of formed products are used as illustrations.

KEY WORDS: formability, rapid solidification processing, recycling, aluminium.

1. Introduction

Recycling is becoming increasingly important because of energy- and material-saving aspects and because it is an effective approach to the problem of environmental pollution. The development and improvement of (new) recycling techniques therefore is of substantial interest.

The recycling of aluminium traditionally has been emphasized, mainly for economical reasons: production of aluminium from bauxite is very energy-intensive and thus expensive. A high recycling rate is achieved for primary aluminium scrap, which is scrap originating from the manufacture of aluminium (semi-)products and therefore has a well known chemical composition. This scrap often can be recycled back into production directly. The recycling of aluminium scrap from discarded products (secondary scrap) is far more problematic. In general this scrap is of an unknown composition, besides it often contains pollutions. A conventional way of recycling secondary scrap is by adding it in the production of casting alloys. The aluminium then has to be separated from compounds and classified with respect to its chemical composition.

At the University of Technology Delft (the Netherlands) a new aluminium recycling technique has been developed, in particular for aluminium from car shredder scrap [2,3,4]. The essential part in this technique is the implementation of a rapid solidification process. By using such a process extremely high cooling rates are obtained in the solidification of the melt, typically in the order of 10^5-10^6 °C/sec. This induces many effects to the material, as a result the properties are entirely different from a conventionally solidified material.

Aluminium car shredder scrap in general consists of various alloys, mainly with high levels of alloying elements (casting alloys, for instance piston alloys), and includes many impurities (oil, remainders of bolts, etc.). If this scrap is recycled by conventional casting techniques, microstructures with a high amount of coarse (intermetallic) second phases are obtained. The material then is very brittle: *it fractures at zero plastic strain*, so it cannot be used in forming operations. Recycling this scrap by rapid solidification processing leads to a refinement of the microstructure and a homogeneous distribution of second phase particles. As a result the ductility is much better (strains at fracture of about 40 %, at room temperature, are common values). The material recycled in this way can be used in subsequent forming operations to obtain a final product.

This paper deals with the forming characteristics of the semi-product, which is reclaimed from aluminium car shredder scrap by using this newly developed technique. To start with, however, the technique will be introduced and some attention will be given to the influence of processing parameters on the properties of the semi-product.

2. Rapid solidification processing of aluminium scrap

2.1. Technique

In this paragraph the new recycling technique for secondary aluminium scrap, developed at the University of Technology Delft, will be described. For a more complete treatment of the technique and its metallurgical backgrounds the reader is referred to publications from the original investigators [2,3,4].

Rapid solidification processing presently is one of the areas for special attention in materials science. By using such a processing route it is possible to alloy compositions which cannot be produced otherwise. Moreover, very fine or even amorphous microstructures are obtained. In Delft the technique is designed especially for the recycling of aluminium scrap from a car shredder plant. The concentrational variations of important elements in the aluminium scrap have been shown to be quite moderate, for a particular shredder. For the scrap a specification is standardized, which is (in wt. %): Si (5.5-6.5), Mg (0.5-1.0), Zn (1.5), Cu (2.8-3.8), Fe (0.7), Mn (<0.3) and Al (bal.). Si and Cu contents are high, mainly due to the large fraction of aluminium casting alloys in the scrap.

In the main step of rapid solidification processing ribbons are produced from a melt by using the melt spinning process. In this process cooling rates of about 10^6 °C/sec are reached by casting the liquid (scrap) metal upon a fast rotating copper wheel. To acquire such high cooling rates it is necessary that the thickness of the produced ribbon is very small: approximately 50 μm. In the present geometry the width is about 3 mm, the length is essentially unlimited.

Subsequent processing is needed to consolidate these ribbons. In a first step the ribbons are cut by a chopper to produce flakes of some millimetres length. For easy handling, these flakes are (cold) compacted to billets in a preform. The actual consolidation takes place by a hot extrusion process: direct extrusion at elevated temperature, using a square die. In this way profiles of various shapes can be produced. The extrusion process especially is suitable for the consolidation of the flakes, since it introduces large (shearing) deformations to the material at high hydrostatic pressure. Both factors are important for bonding the flakes: the oxide layers at the surfaces have to be stripped, then the flakes can be "welded" together. The material obtained is of a 100 % density.

The profiles produced in this way can be used directly, for instance for construction purposes, but they also may serve as an input material for forming processes. The formability of the material then is of particular interest.

2.2. Influence of processing parameters

In the recycling technique as described above many processing parameters are involved. Parameters in the melt spinning process are the wheel velocity (which determines the cooling rate) and the temperature of the melt. The cold compaction step introduces the billet density as a further parameter. Concerning the hot extrusion process, the extrusion temperature, the extrusion ratio and the preheating time before extrusion are variable.

Earlier investigations were done into the influence of the processing parameters: wheel velocity, temperature of the melt, time interval between melting and melt spinning, preheating time before extrusion and extrusion temperature [3]. Processing influences were evaluated from the mechanical properties: hardness, yield strength, ultimate tensile strength and elongation. It was concluded that these properties are mainly determined by the extrusion conditions, provided that the cooling rate during melt spinning was sufficient.

So the extrusion temperature is an important process parameter. In this paragraph some attention will be given to the influence of this parameter with respect to the plastic properties of the semi-product obtained.

The input material for the hot extrusion was melt-spun on a pilot scale plant at the standard conditions [4]. The composition of the scrap was in accordance with the previously mentioned specification. Extrusion was done on a laboratory press. The diameter of the billets was 30 mm; the extrusion opening was circular, so the extrusion product was a round bar. From these bars torsion specimens could be taken. The extrusion ratio had to be relatively low (R=9 , bar diameter: 10 mm), otherwise the diameter of these specimens would be too small.

Melt spun aluminium scrap was extruded at 385, 400, 450 and 500 °C. This range was confined to a minimum by the press capacity and to a maximum by the heating equipment. In a first condition material was used without a previous cold compaction: flakes were just loaded in the extrusion chamber. In a second condition the materal was previously cold compacted to billets with a relative density of approximately 85 %, a value that could only be reached by applying a very high pressure. These conditions can be seen as representing the (cold) pre-compaction limits. The material was tested in the as-extruded condition.

In the first instance, the hardness distribution over the cross-section of the extruded bars was measured to see if there were any variations as a result of the local extrusion conditions. For this purpose

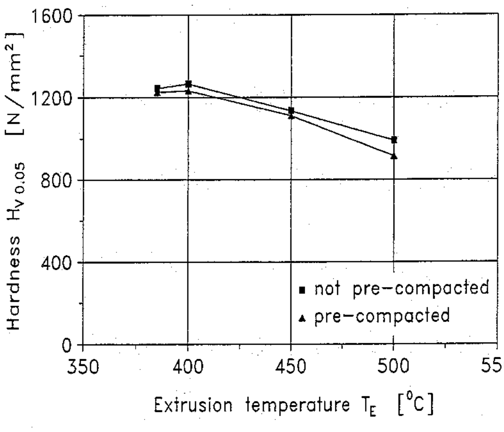

Figure 1 Hardness of extruded bar as a function of the extrusion temperature

the micro-Vickers test was used. Measured variations, however, were found to be not significant; obtained values therefore were averaged. The resulting average hardness is shown as a function of the extrusion temperature in **figure 1**. Both conditions (pre-compacted and not pre-compacted) are included in this graph. As can be seen from this figure, the hardness of the extruded semi-product is lower when the extrusion is done at a higher temperature. A further observation is that differences between the two conditions are only marginal, if not absent. Obviously the relative density of the billets has no significant influence on the hardness of the extruded semi-product.

A similar conformity between the two conditions was found when the results of torsion tests were compared. These results here are presented without a further separate treatment of the pre-compaction condition; values for both conditions are averaged. The torsion tests were performed at room temperature and quasi-statically.

The moment-twist curves were recorded; from these the corresponding flow curves are derived. These curves can be characterized globally in terms of C- and n-values according to the Hollomon flow function ($\bar{\sigma}_f=C\cdot\bar{\varepsilon}^n$). The influence of the extrusion temperature on the flow behaviour of the semi-product can be summarized as a limited decrease in characteristic stress from C=530 N/mm^2 at T_E=385 °C to C=470 N/mm^2 at T_E=500 °C, whereas the strain hardening exponent approximately remains constant at n=0.15.

From these torsion tests also the strains at fracture have been determined. The quantity is defined as the effective strain at the moment of failure. In a torsion test, the strain at fracture is determined by the strain for the outer radius of the specimen at fracture. In **figure 2** these values are shown as a function of the extrusion temperature. From this figure it follows that the strain at fracture is higher when the material is extruded at a higher temperature. This might indicate a better bonding

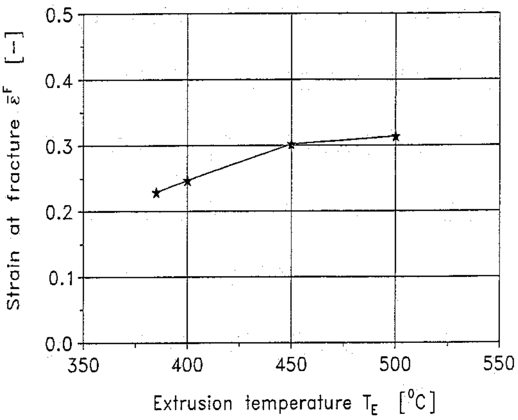

Figure 2 Strain at fracture of extruded bar as a function of the extrusion temperature (torsion tests)

between the original flakes.

This paragraph will be concluded with a short recapitulation. Rapid solidification is, in fact, a quenching operation, not from the solid but from the liquid state. This induces many metallurgical effects to the material and, consequently, acts on its properties [2,4]. When the material is re-heated, like in the extrusion process, the properties are influenced. A high extrusion temperature leads to a devaluation in mechanical properties like hardness, yield strength and ultimate tensile strength ([3] and figure 1). With respect to the plastic properties of the extruded semi-product, however, a high extrusion temperature is rather profitable: flow stresses are slightly lower, ductility is better.

3. Formability of recycled aluminium

In this section the attention will be focussed on the formability of the semi-product recycled from aluminium secondary scrap. Recycling was done by rapid solidification processing on a pilot unit at the standard conditions [4], using scrap with a composition according to the standard. The extrusion is done on an industrial press at a temperature T_E=450 °C, extruding the billets (ϕ110 mm; pre-compaction of approximately 60 % of full density) with an extrusion ratio R≈30. The die opening is such that a profile with a dumb-bell shaped cross-section is produced; from this both sheet and bar can be extracted for experiments. Test pieces were annealed in air for 20 minutes at 350 °C. This heat treatment was done to reduce the internal stresses caused by machining, but it also showed to have a marked (positive) influence on the plastic properties. The presented results in this section, anyhow, are restricted to the investigated condition.

In order to acquire information about the formability of this material a number of tension and torsion tests is performed. In these tests the temperature is varied in a wide range. Two sets of tension tests were done; test specimens respectively were taken longitudinal (bar) and transverse (sheet) from the extruded profile. These experiments were complemented by a third set: torsion tests on specimens, taken from the bar-sections of the profile. All tests were done quasi-statically and in triplicate; represented values are averages.

The flow curves derived from these sets of experiments can be

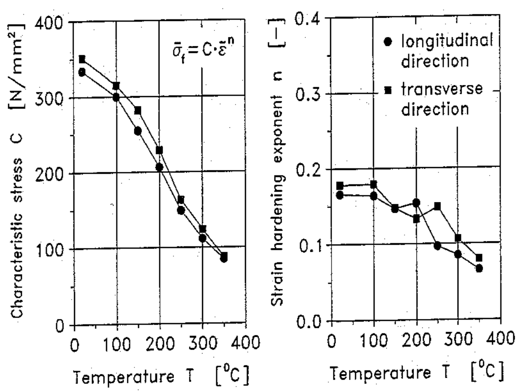

Figure 3 Flow curve characterization of extruded profile as a function of the temperature (tension tests)

characterized by the Hollomon flow function ($\bar{\sigma}_f = C \cdot \bar{\varepsilon}^n$). In **figure 3**, the characteristic stress C and the strain hardening exponent n, as determined from the tension tests in both directions, are shown as a function of temperature. Differences in flow behaviour between the longitudinal and transverse direction are only marginal. The characteristic stress in particular depends strongly on the temperature.

The strains at fracture, derived from the tension tests in both directions, are represented as a function of the temperature in **figure 4**. Values shown in this figure are local values: determined from the neck of the test pieces. At first it is noticed that the strains at fracture increase

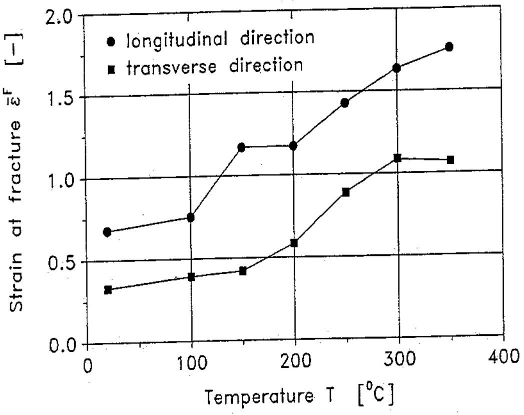

Figure 4 Strain at fracture of extruded profile as a function of the temperature (tension tests)

for increasing temperature. Further, there are significant differences between the fractional strains in the two directions. These differences are closely bound up with the nature of the consolidation of the flakes: the extrusion process leads to a pronounced orientation of the original flakes in longitudinal direction. When the material is strained in a transverse direction, the bonding surfaces are loaded perpendicularly; this is unfavourable as compared to straining in longitudinal direction. For practical purposes, this means that the ductility of the material is restricted by the properties in transverse direction.

An attractive way to represent the ductility of a material as a

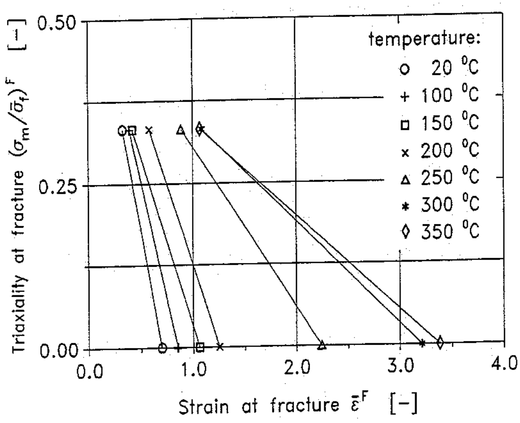

Figure 5 Failure curves of recycled aluminium, using the temperature as a parameter

function of the state of stress is by means of a failure curve [1]. This is a curve of the equivalent strain $\bar{\varepsilon}^F$ versus the triaxiality $(\sigma_m/\bar{\sigma}_f)^F$ at ductile failure and can be determined by some standardized tests (triaxiality is the ratio of the mean stress $\sigma_m=(\sigma_1+\sigma_2+\sigma_3)/3$ and the effective flow stress $\bar{\sigma}_f$. It is possible to estimate the failure curves from the results of the tension and torsion tests (**figure 5**). For tension, the values from the tests in transverse direction are used. The triaxiality at failure in these tests is approximated by the value for a uniaxial stress state $(\sigma_m/\bar{\sigma}_f)^F=1/3$; in a first instance this is considered acceptable while necking occurs rather diffuse. For torsion, on the other hand, $(\sigma_m/\bar{\sigma}_f)=0$

during the entire test. From figure 5 it follows, that the ductility of the material approximately duplicates in the range between room temperature and 200 °C; the most significant improvements, however, manifest between 200 and 300 °C. From 300 °C on no further increase in ductility is observed.

Figure 5 can be used as a guide-line in determining the proper conditions for a forming process. For instance: if strains and stresses can be assessed for a particular process, it is possible to estimate the required minimum temperature to obtain a sound product.

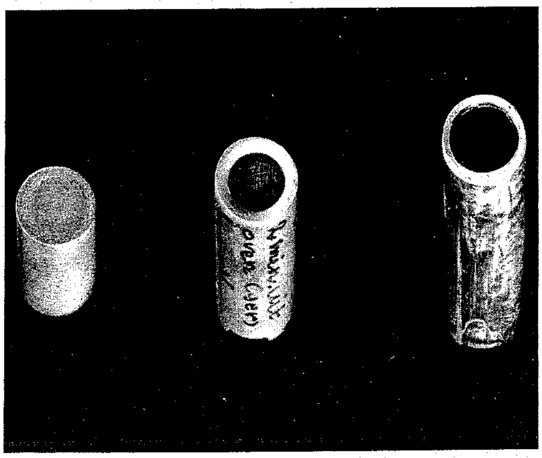

Figure 6 **Products of recycled aluminium, formed by backward can extrusion**

Processes which proceed (globally) under a hydrostatic pressure are favourable with respect to ductility. One of these processes is backward can extrusion; examples of products formed by this process from recycled aluminium are given in **figure 6**. In the left part of the photograph a billet is shown (ϕ12 mm; height: 16 mm) machined from the bar section of the profile. In the middle and right part of the photograph two cans are reproduced, extruded from the billet with an extrusion ratio of R=1.8 and R=3.3 respectively (corresponding wall thicknesses of 2 and 1 mm). The bottom thickness of these cans is approximately 1 mm. These cans were extruded at a temperature T≈250 °C.

4. Conclusion

Rapid solidification processing is a promising new technique for the recycling of secondary aluminium scrap. The rapid solidification step leads to an extremely fine and homogeneous microstructure as compared to the conventionally solidified material; as a result the mechanical properties are entirely different.

The hot extrusion parameters are important with respect to the properties of the semi-product: they both determine the extent to which the induced metallurgical effects are preserved and the bonding between the flakes. A high extrusion temperature is favourable when the material is subsequently processed by forming operations. The properties of the semi-product further can be influenced by heat treatments.

In the present work one condition of the semi-product was investigated with respect to the formability. The strains at fracture in longitudinal and transverse direction, determined from tension tests, show significant differences. Corresponding flow curves, on the contrary, are practically the same. The ductility of the material is determined as a function of the temperature by means of failure curves. From this it is possible to evaluate the proper conditions for a particular forming process.

Products are produced from the recycled semi-product by backward can extrusion at elevated temperature.

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