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Aluminium is a readily deformable metal and, even when alloyed to achieve acceptable engineering mechanical properties, retains sufficient malleability to allow deformation processing, hot and cold, into thin or complex shapes by rolling, extrusion or forging. The world now takes for granted aluminium foil, thin section extrusions and aerospace forgings, each of which was a marvel in its day, and each of which has required much empirical work to define the process route to achieve acceptable mechanical properties and, hence, it is assumed, microstructure. Indeed, the very complexity of many shapes in aluminium has largely hindered the use of any simulation technique to help optimize these products, including modelling, until very recently. Even now, the tortuous strain path followed, for example, by a volume element undergoing extrusion through a port-hole die even defies analysis, let alone simulation, and empiricism must reign.

For the more simple geometries of rolling and, to some extent, forging, these more clearly constrained strain paths allow closer analysis, simulation and, albeit at the early stages, modelling, of the development of microstructure and properties in the cold-rolled or hot-rolled state. This paper considers the needs of the aluminium industry, as defined by the end-product (customer) requirements. Predicting the development of the deformed state, in terms of the driving force for subsequent recrystallization and microstructure and crystallographic texture development during deformation, will be considered, together with the subsequent control of annealed structure and properties, including crystallographic texture. Consideration will also be given to the on-line measurement of microstructure and properties with implication for online control during manufacture. It will be shown that a combined approach using physical, as well as numerical, models, allows for the successful development of new products and the supporting scientific discipline.

Keywords: aluminium metallurgy; hot rolling; simulation; modelling; texture; microstructure and properties

1. Introduction

In the aluminium industry, many semi-fabricated products are required to meet demanding specifications, specified by the customer, for downstream processing as well as final-product properties, and, in general, these must be processed by the correct thermomechanical schedule to ensure the specification is met. This is particularly true for commodity products, such as strip for the manufacture of beverage cans, where the forming process can be likened to the application of an identical, and very exacting, product test across the entire strip area, as cans are made in

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high-speed processing. Any interference with the smooth, and fast, running of the can manufacturing line is, according to the specification, sufficient for the customer to be able to return the coil as scrap. Such critical products also tend to make up the bulk of any product mix, since it is the large tonnage, commodity, markets (e.g. can body, can end, foil), which demand the utmost in material consistency and adherence to specifications. The specifications for these products have, of course, developed as the product has developed, and, as the forming operation has become more severe in its requirements, so the aluminium industry has responded with more sophisticated strip to meet the challenge. Clearly, this empirical approach to product development, based on evolution and plant trials, is both expensive and time consuming. As new markets are sought for aluminium, often as a substitute for an existing semi-fabricated product, the exacting product requirements are encountered earlier in the time-scale of product development, and more advanced methods of defining the product chemistry and manufacturing route are needed, before full-scale line trials, to replace the largely empirical nature of product development previously used in the industry.

The dream, or vision, of course, is to be able to predict the effect of a particular alloy chemistry, being processed by a particular thermomechanical treatment, on the forming behaviour of the semi-fabricated product and the mechanical properties of the final product. Such predictions are often thought about solely from a numerical modelling viewpoint, although it should be realized that any ‘model’, be it numerical or physical, that can help elucidate part of the problem will find a use in industry. From the outset, it must be realized that, in many cases, the detailed physical metallurgical understanding behind any composition or process of manufacture may not be adequately known. So-called ‘models’, which seek to predict, via some functional relationship between composition or process and measured response on properties, may be used for interpolation with care, but, when used for extrapolation, are frequently found to be wanting owing to the total lack of a real physical basis for the functional relationship employed. To a large extent, the traditional properties of strength, ductility and even toughness can be controlled using functional relationships to composition and processing, based on sound metallurgical principles, determined over many decades. However, although such properties are important in determining the in-service suitability of the final product, in the semi-fabricated form they rarely indicate how the downstream ‘processability’ in the customer’s process will be affected. To do this we must understand how to control a whole range of properties that are loosely defined by terms such as ‘formability’ and ‘runability’, and which refer to the ability of the product to adequately accommodate the forming operation successfully *and run on the customer’s production line*. It should be noted that these attributes of the product associated with ‘processability’ are more closely linked to the thermomechanical processing of the strip than are the relatively simple properties such as strength, which can be more dependent on composition.

The important driver behind the desire to predict any effect of compositional or process change on product performance is cost reduction. Traditionally, the empirical development of a new product has served well in the time-scales available, but, nowadays, this would be too expensive for any new product, especially one designed to substitute into an existing market. There are several reasons for this. One is that the unit of metal being processed by modern aluminium plants is constantly increasing. Ingots weighing up to 25 t are now commonplace for commodity products such as beverage can stock and foil stock. Another is the huge cost in productivity and logistics of fitting small trial orders into the day-to-day running of modern production facilities. Thus, for new products, the aluminium industry needs to have a predictive capability to enhance the ability for off-line development before the eventual need for plant trials in the final stages of product development. In addition to this, even for mature products, process routes for semi-fabricated products continue to evolve, driven by economics or logistics, and the impact of any proposed change needs to be assessed before implementation to allow the metallurgists time to develop the process refinements to ensure consistency of the product throughout the period of change. It should be emphasized that it is always assumed that the metallurgy, and other aspects of the product, can always be corrected when these cost-effective process-route changes are developed!

With cost reduction as the key driver behind the need for process simulation (i.e. physical modelling) or process modelling, it is not difficult to see why there is so much current interest in the development of predictive capabilities of all descriptions.

2. Current application of process models in the aluminium industry

Perhaps the oldest property of hot or cold deformed aluminium strip which has been subjected to the development of predictive capability as described above, is thickness, or ‘gauge’, and the associated ‘profile’, or gauge across the width of the strip. This property is now automatically controlled on all modern rolling mills, and it is pertinent to examine the requirements necessary to allow such control systems to function. Firstly, the property, strip thickness, may be measured to a reasonable degree of accuracy by using the radiation absorption characteristics of the alloy with either a single sweeping sensor or a parallel series of sensors positioned across the width of the strip. Thus, the first requirement of any process control is available: the ability to measure, on-line and in real time, the property of interest.

Thickness measurement may be conducted at the exit of the mill and the signal used to develop feedback control to control the strip gauge. More desirable is the ability to also measure the strip thickness before the mill entry: to detect gauge variations in the incoming strip; and allow feedforward control to the mill for much closer control of strip thickness. Whatever method is adopted, a ‘model’ of the effect of any change determined as part of the control strategy is desirable to predict the effect of change before implementation, as illustrated in figure 1. This model could be a simple transfer function for the mill, which is a quantitative functional relationship of the effect of the proposed change on the strip thickness, and could be determined empirically for any mill, given the relative simplicity of the response to the control action (i.e. the compliance of the rolling mill). With an accurate transfer function, corrective action can be applied without overcompensation and the development of inevitable oscillations in strip gauge.

For the control of profile, the industry resorts to the use of much more sophisticated models and control actions during hot rolling. With the gauge measured as a function of strip width, appropriate action is taken either to physically bend the rolls, using hydraulic jacks, or to alter the spray pattern of the lubricant emulsion, which effectively alters the local roll radius by changing the local roll temperature. Such thermal control of the roll gap allows accurate and rapid adjustment of the local strip thickness and is the central concept behind modern control systems, although

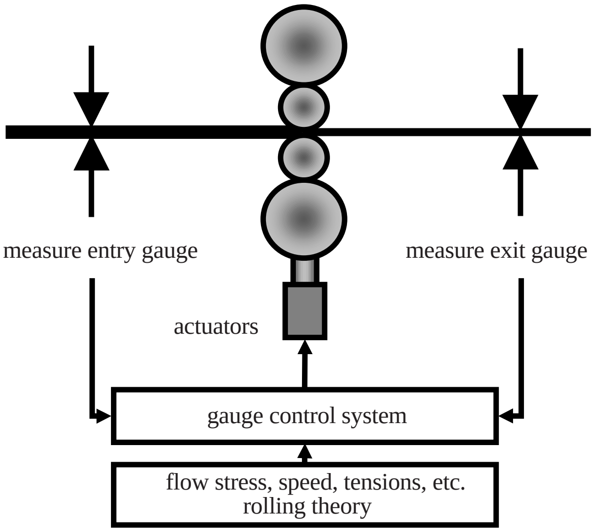

Figure 1. Schematic diagram illustrating the key features of automatic control systems for strip geometry.

true closed-loop control by this means is rarely employed. Thus, for profile control, much more complex models are required, which rely on a relatively well known and understood materials property, thermal expansion of the roll steel, for which extensive databases either exist or could easily be determined. By this means, it is possible to develop a predictive effect of the changing lubricant spray pattern on the roll gap shape and, thus, control the exit-strip profile.

These examples of the control of the physical property of strip geometry serve to illustrate the fundamental requirements of the successful use of predictive models in the aluminium industry. Firstly, the ability to measure, on-line and in real time, the property of interest: strip thickness. Secondly, to have an understanding of the physical principles that lie behind the control strategy, to enable a model to be constructed to predict the effect of the control action on the property of interest. Thirdly, to have built into the mill control, actuators that allow the on-line change of the property once the control action has been calculated. With these three requirements in place, modern control of gauge to *ca.* 0.5%, and of profile to less than 1% of strip thickness, is now a standard requirement for most commodity products.

3. Control of metallurgical properties during deformation processing

If the logic described above is examined in light of the requirements for the control of any metallurgical property, it rapidly becomes apparent that key elements are missing. Even if we take an important property with real economic ramifications, if deviation from specification takes place, such as the control of anisotropy of mechanical properties as a result of crystallographic texture development during processing, this is still, unfortunately, true. Measurement of texture on-line and in real time is feasible, and for the development of deformation textures during rolling may be used, although not commonly in the aluminium industry. This is largely because the real desire is to be able to predict the textures formed as a result of an annealing practice deployed after rolling to soften the material, both to enhance the ability to process the strip to final gauge and develop the correct mechanical properties. With the knowledge we have today, it is difficult to see how the measurement of deformation textures can assist in predicting the final annealed textures, which result from the heat treatment after rolling, and which can only be measured some hours after processing. Obviously, actual measurement of the recrystallization texture is of no use in developing a control strategy, since the critical process stage concluded long before the measurement could be taken. Even if a real correlation could be determined between the development of deformation textures and recrystallization textures, and assuming on-line texture measurement was sufficiently accurate to record the subtle differences developed during the process, our current understanding of the effect of rolling process parameters on texture development is insufficient even to begin thinking about developing a control strategy. Finally, if a control strategy, including a predictive model, were to be available, it must be incorporated into the existing control strategies for gauge, profile and other geometric considerations, none of which may be compromised for better metallurgical control. Having indicated the difficulties involved in controlling the metallurgy of the product, it should be emphasized that in certain industries, notably steel and copper, anisotropy and grain size may be controlled during production, but at present this approach is not employed in the aluminium industry.

Obviously, a different approach must be developed in order to control the properties, and other characteristics, of the product, and the approach usually adopted is to define a window of acceptable process parameters that will adequately develop the required properties of the product. The task of metallurgists and surface scientists is to provide a description of that process window, within which the on-line control strategies for product geometry may be employed. This is where the use of any form of predictive capability is most cost-effective, since the process window can be defined before the need for expensive plant trials. Even so, the final description of the process window can only be done on the mill, so the real challenge is to reduce the amount of mill time required to develop an acceptable product for the known specification.

4. The development of process windows for product manufacture

The industrial research scientist has a range of techniques available, at least in theory, to evaluate the potential of any process or compositional development or change, and all fall within the broad description of 'predictive capability', and may be used to avoid total reliance on 'blind' plant trials. These techniques form a hierarchy (Ricks *et al*. 1994) of the development of process control, as follows.

Physical simulation of the plant process This is a very old tool, often used in laboratories for the evaluation of heat treatments, although nowadays the term is usually reserved for more sophisticated techniques used to simulate thermomechanical deformation during processing. The use of physical simulation does not require any knowledge of the events taking place during the process, and the very use of this approach may indicate a total lack of any physical understanding of the effects of the process on the development of microstructure and properties in the product.

Physical simulation may also be termed ‘physical modelling’, and can give a predictive capability.

Curve fitting to data developed from real plant trials or, if accurate enough, from a physical simulation of the process stage of the plant in the laboratory Again, this is an old approach to archiving any empirically developed ‘functional relationship’, linking chemistry or process stage to the property of interest, or to the characteristic of the product (e.g. grain size, dislocation density, etc.) if that is of interest. Despite not having any requirement of knowledge behind the form of the curve fitted to the data, it is quite surprising how often this approach is enthusiastically referred to as modelling. A more modern development of this approach is to explore multi-dimensional problems using neural networks. The benefits of using these approaches lie in the ability of the techniques to reveal the existence, and possibly the form, of a functional relationship between chemistry or process, and property or characteristic of the product. As already mentioned, curve fitting can give, at best, an ability to interpolate: extrapolation from an existing data-set is usually not recommended.

Development of a ‘working hypothesis’, usually as a result of curve fitting to experimental data derived from plant trials or physical simulation of the process step This is an important step in the development of the science base of the subject area and usually requires a great deal of knowledge of the material characteristics and behaviour under the conditions prevalent during the stage of processing of interest. Many examples exist in the literature, and the collection of such working hypotheses, especially when proven, constitute the science base behind any discipline such as metallurgy. Relevant examples to the topic of this paper include particle-stimulated nucleation of recrystallization and the ability of certain crystallographic orientations to ‘survive’ deformation by rolling in aluminium, which will be explored in more detail in subsequent sections.

Development of physically based models of the effect of the process on the development of product characteristics (e.g. microstructure), and which can subsequently be related to the property of interest Such physically based models often derive from an initial working hypothesis, as defined above, and, in reality, constitute the highest level of understanding available in the applied sciences relevant to deformation processing. In practice, it is rare that all parameters needed for the successful completion of such models are known or can be easily measured. Well-known (notorious?) examples include diffusion coefficients, heat transfer coefficients and, of course, friction. Usually, to make such models predict to the level of accuracy required to be valuable, they must be ‘calibrated’, or fitted, to real data, again either from real plant trials or accurate physical simulation, and, as such, have been referred to as ‘intelligent curve fitting’ (Ricks *et al*. 1994), since the form of the fitted curve is derived from a sound knowledge of the physical events taking place during the process. This inherent feature gives some confidence in the ability to extrapolate beyond the data-set available for calibration and, as such, constitutes a real predictive capability. An intrinsic part of this type of model is the successful development of simplifying assumptions, which are inevitably needed to make the mathematics of the model simple enough to work without corrupting the accuracy of output data. Such assumptions are usually material specific.

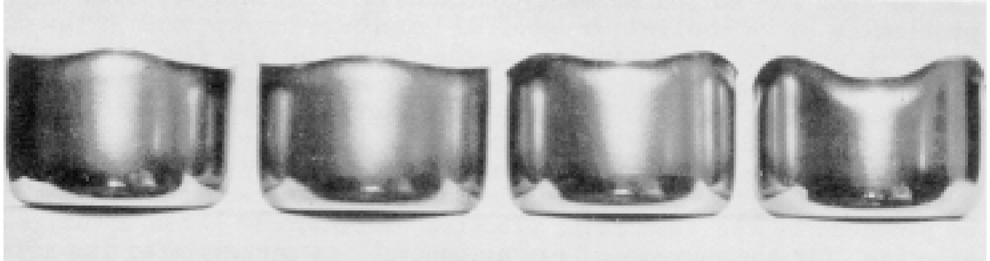

Figure 2. Drawn aluminium alloy cups showing symmetrical protrusions on the rim, known as 'ears', caused by the crystallographic texture present in the material.

This hierarchy of techniques of simulation, as indicated throughout the above description, is interrelated. Probably the most powerful tool in the modern industrial scientist's arsenal is to combine the use of these techniques to provide data in the right time-frame to be useful in new product development, or existing process or chemistry change. The time-scale issue is interesting. Successful application of physical simulation can give rapid results available for immediate implementation in the plant. The derivation of functional relationships from such work, leading to the development of working hypotheses, over a longer time-scale, provides valuable information and knowledge that is often applicable across a wide range of alloy and product types (and adds to the science base of the discipline). Finally, the formulation of a physically based model, calibrated with real or simulated data, should be seen as the ultimate culmination of knowledge and expertise, and may take many years to bring to fruition. In the world of industrial research, the early success derived from the physical simulation approach can lead to the development of individual or group credibility sufficient to allow the continuing development of working hypotheses and physically based models. It is now pertinent to examine the use of this approach in developing a predictive capability for an important property, already mentioned in a previous section: anisotropy caused by crystallographic texture. This is important in the control of 'earring' in beverage-can alloys, and the ratio of thickness to width strain ('r-value'), which influences the forming behaviour of all sheet products.

5. Crystallographic texture control in aluminium alloys

Perhaps the most widely known application for texture control during the manufacture of aluminium strip is for material destined to become beverage cans, known as 'canstock'. This is invariably made from an Al–Mg–Mn alloy, with deliberate additions of Fe, Si and Cu to provide the correct balance of strength, formability and ability to be recycled. Canstock is supplied to the canmaker in a fully cold-rolled condition ('extra hard'), and one small marvel of this product manufacture is that the draw and wall-ironed (DWI) can has a process route engineered such that at no time is tensile plastic strain required to form the can: as supplied, the tensile ductility of canstock is *ca.* 3%. Modern can lines are capable of making in excess of 300 cans per minute, and in North America alone, *ca.* 2.5 million tonnes of metal are consumed annually. Texture control is necessary to minimize the formation of 'ears' in the drawn cup (figure 2), which are exacerbated by the wall-ironing operation to maximize the depth of the can, and which must be trimmed off before the can end is

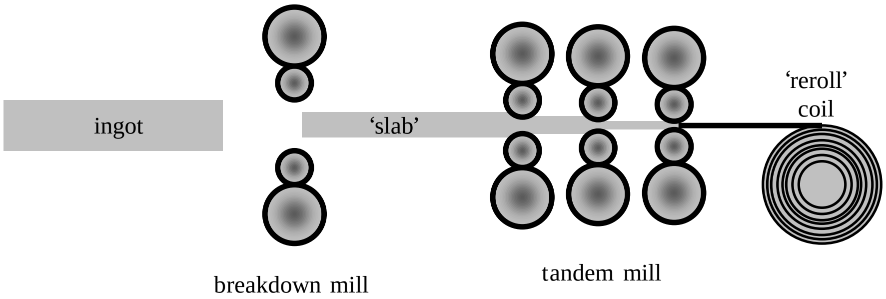

Figure 3. Schematic diagram illustrating the process route for the hot rolling of aluminium alloys such as AA3004 for beverage can sheet.

added. The trimmed material constitutes waste, and if the degree of earring is high, the waste is also high. As the canstock product has been developed, the metallurgists have learnt that the texture developed by slip during cold rolling, which develops ears at 45° to the rolling direction, can be balanced if the hot-rolled product has an adequate quantity of texture components that promote ears in the rolling and transverse directions of the strip. Two texture components may be highlighted for control in the hot-rolled product: 'cube' texture and 'Goss' texture, and the former has developed an almost fanatical following among metallurgists devoted to the understanding of its origin. This understanding is still being developed, and, as such, provides an excellent vehicle for the adoption of the aforementioned strategy for the development of control plans for the manufacture of canstock.

(*a*) *Physical simulation of hot rolling of aluminium*

Modern aluminium rolling mills typically consist of a single stand, four high, reversing mill used initially to deform the 600 mm thick ingot into a slab *ca.* 30–40 mm thick. This slab is then fed into a multi-stage 'tandem' mill for the simple reason that the slab length becomes too long to be handled if reversing rolling were to be continued. On exit from the tandem mill, the strip is coiled before cooling down to ambient temperature for cold rolling. This process route is illustrated in figure 3. It is the thermomechanical processing in the tandem mill that leads to the greatest opportunity for the control of crystallographic texture. Of particular interest for the metallurgist is the sequence of strain (rolling reduction), strain rate (speed at each stage) and temperature, together with the time-intervals between successive deformations and the thermal history of the final anneal, which are the key parameters in the control of microstructure and texture.

Plane-strain compression testing (Sellars *et al.* 1978) is a popular method of simulating rolling, given the similarity of the strain path of the technique and the centreline of a rolled strip. This similarity prompted Alcan International Ltd to develop the technique (Bolingbroke *et al.* 1993) to allow the entire simulation of the strains, strain rates and thermal histories associated with multi-stand rolling, with a view to using the simulation process to simulate the development of both deformation and annealing textures in hot-rolled and annealed aluminium. Subsequent investigations have shown that, provided the correct strain, strain rate, temperature, time-interval and annealing temperatures are used, surprisingly accurate simulations of crystallographic texture can be made, as shown for the case of beverage-can alloys in figure 4.

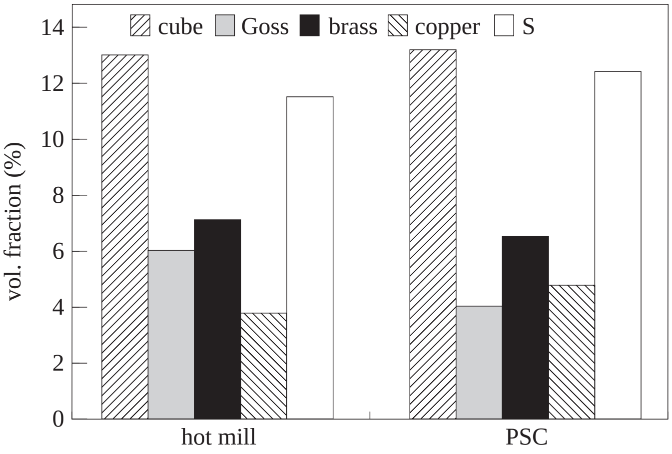

Figure 4. Simulation of texture components in hot deformed aluminium alloy AA3004: textures produced by hot mill processing are shown on the left, textures produced by plane strain compression (PSC) testing are shown on the right.

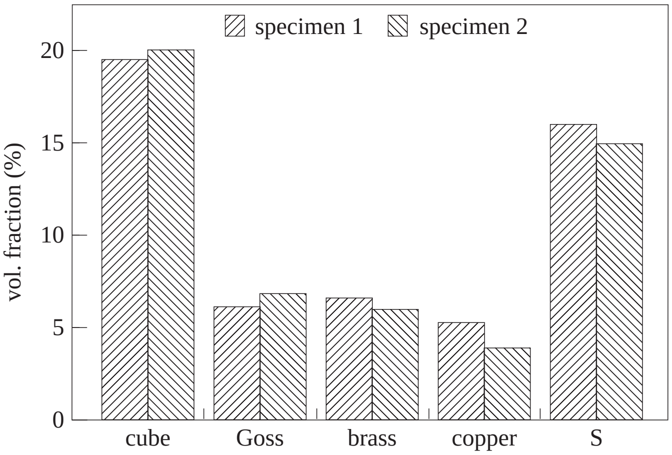

Figure 5. Physical simulation of the effect of introducing a fourth stand into a tandem mill on the textures developed in hot deformed AA3004 (cf. figure 4).

Of much greater interest is the potential for using this technique to simulate potential changes to the production route, or, for that matter, completely different production routes for this product. Figure 5 illustrates the simulated textures developed by the introduction of a fourth stand, for productivity improvements, as has happened in Alcan's major rolling plants in Germany and the USA. Such information allows changes in product chemistry and process route to be determined to maintain balanced textures at final gauge to meet the exacting earring specification for the product. The successful deployment of this technique has helped pave the way for a continuing, and highly regarded, programme of research into the development of microstructures and textures in hot-rolled aluminium alloys in Alcan's research and development laboratories, with significant involvement of universities in Europe and North America.

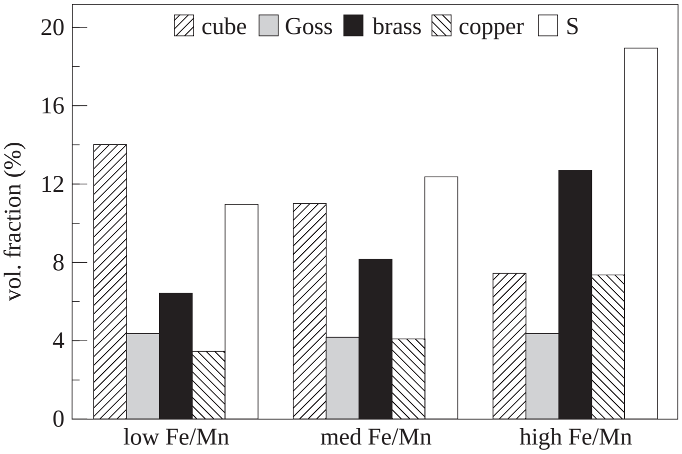

Figure 6. Effect of iron and manganese levels in AA3004 beverage-can sheet on the crystallographic textures produced by simulated hot rolling by plane-strain compression testing.

With the ability to simulate a key part of the process route for hot rolling of aluminium alloys now established, there is the real possibility of exploring some of the key parameters that control texture and, ultimately, earring. One obvious example is composition: during the late 1980s, a major hot mill in North America only resolved issues with earring control by reducing the iron level in the alloy after an extensive series of costly plant trials, thus limiting the potential to use recycled metal and increasing costs. Figure 6 shows the effect of alloy composition on the development of annealing texture components after simulated hot mill processing using plane-strain compression testing experiments. Clearly, these data indicate that as the iron level is lowered, the level of cube texture increases and the material is able to accommodate the cold rolling strains to final gauge and final strength targets without the development of excessive rolling textures and high earring levels. This was the effect exploited by the plant in North America, but the knowledge has been developed in the laboratory at far lower cost.

Similarly, the effect of process conditions may be explored using the simulation facility, again at much lower cost than real plant trials, and with the added advantage that material may be processed through only part of the real process stage, thus allowing for the development of microstructure to be understood. The initial hot rolling of aluminium (figure 3) is carried out at relatively slow strain rates and high temperatures in a 'breakdown' mill, so called because of the original function of breaking down the as-cast microstructure of the ingot. Under these simulated conditions, it may be seen that the cube texture, usually considered to be unstable by rolling processing, may survive the hot deformation and, thus, play an active role in assisting the nucleation of cube texture in the recrystallized product, as shown in figure 7. Also illustrated in figure 7 is the much lower stability of this texture component at high Zener–Holloman parameters (low temperature, high strain rates) associated with the tandem mill rolling of these alloys. Furthermore, the role of microstructure may be deduced, and figure 7 also shows the effect of a coarse or fine precipitate structure on the stability of the cube texture, even at low Zener–Holloman parameters, with fine precipitates destabilizing the cube texture during deformation.

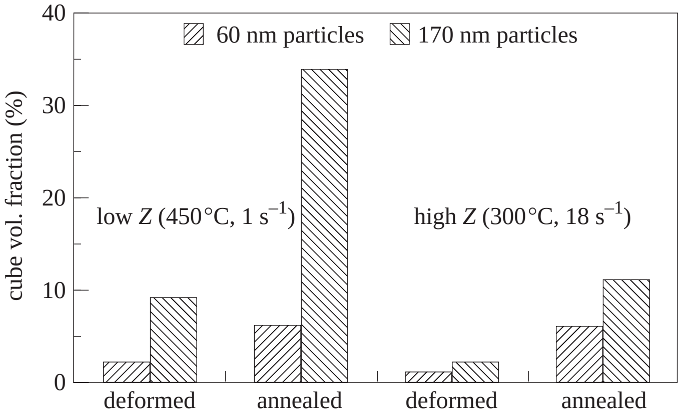

Figure 7. The effect of deformation conditions and microstructure (precipitate size) on the stability of cube texture in AA3004 during simulated hot deformation conditions by plane-strain compression testing.

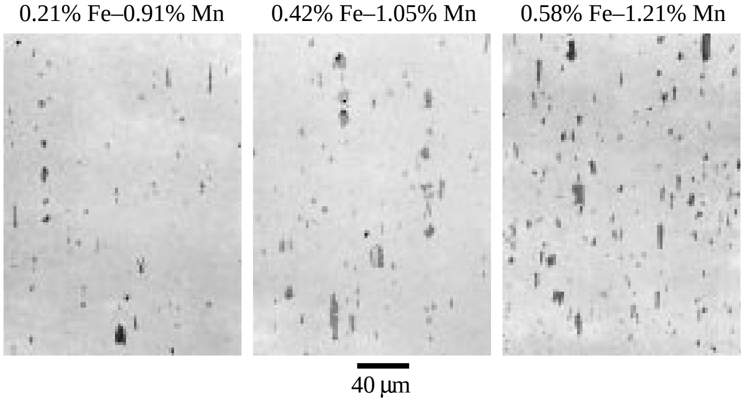

Figure 8. Light optical microstructures (unetched) showing the effect of iron and manganese on the intermetallic volume fraction in AA3004 as used for beverage-can manufacture.

(*b*) *Derivation of functional relationships for hot rolling of aluminium*

As shown above, with a proven ability to simulate the complex deformation process involved in multi-stand hot rolling, it becomes possible to explore the features of the process and the chemistry that control the development of both microstructure and properties. This information is of great use in understanding the effect of process and chemistry on the properties of the material, but requires reduction to a more basic form to allow understanding of the phenomena responsible. For example, if the microstructures of the AA3004 material used in the aforementioned simulations are examined, it becomes obvious that the primary effect of adding higher levels of iron and manganese to the alloy is to increase the volume fraction (number density) of coarse intermetallics, as shown in figure 8. Examination of the material after simulated deformation and annealing reveals that one response of the microstructure to this change in alloy chemistry is the creation of a much finer recrystallized grain size, as shown in figure 9. The obvious conclusion is that the particles are responsible

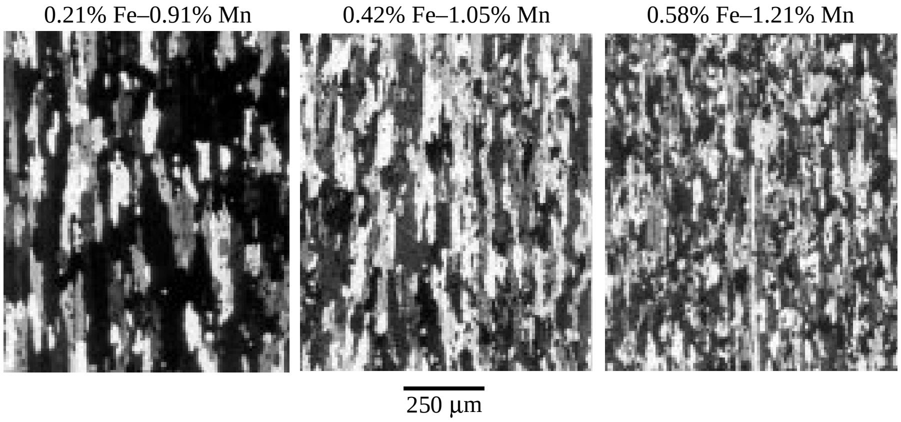

Figure 9. Light optical microstructures (Keller's etch) showing the effect of iron and manganese on the post-deformation anneal grain size in AA3004 as used for beverage can manufacture.

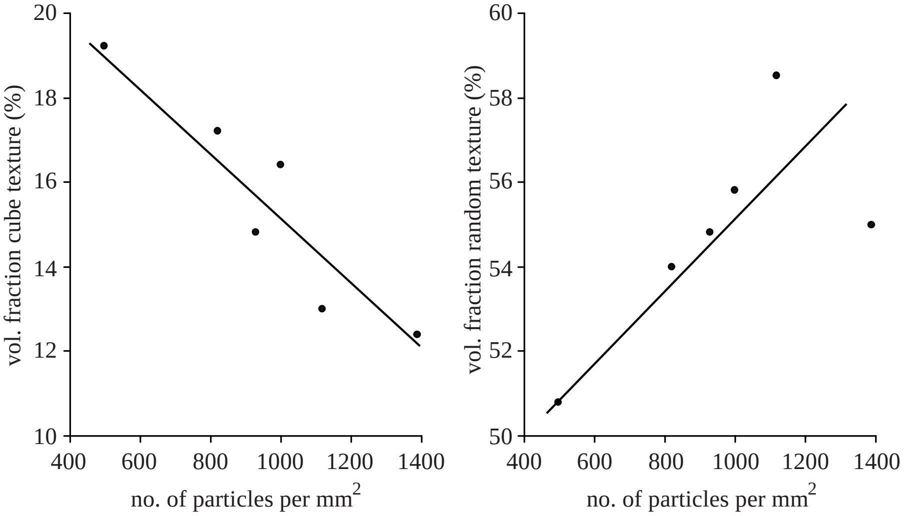

Figure 10. Effect of number density of particles capable of nucleating recrystallized grains on cube texture (left) and random texture components (right) in AA3004 alloy deformed by plane-strain compression test simulation of hot rolling.

for the nucleation of many more grains under the simulated deformation conditions and, thus, functional relationships may be derived for the effect on number density of critically sized particles on the volume fraction of cube texture developed, as shown in figure 10. Examination of the data in figure 10 reveals that the fundamental effect of the coarse intermetallics is to enhance the nucleation of random-texture components that grow at the expense of the cube-texture component. In this form, the information is readily archived, even embedded in some form of 'model', without any fundamental understanding of the processes taking place, although, in this example, the working hypothesis is that of particle-stimulated nucleation (PSN) of recrystallized grains (Humphreys & Hatherly 1995).

Simulation of the conditions of breakdown mill rolling (low Zener–Holloman

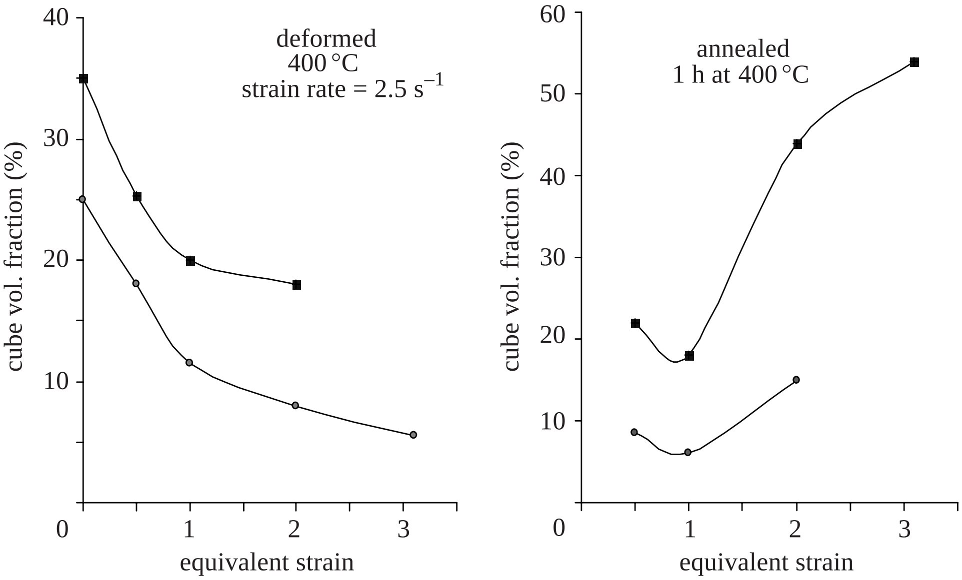

Figure 11. Functional relationships for the effect of total equivalent strain on the survival of cube-texture components (left) during deformation of AA1050A alloy, and the subsequent growth of this texture component during annealing (right) to a fully recrystallized microstructure.

parameters), as discussed in the previous section, yield functional relationships of the type shown in figure 11, which illustrates the phenomenon of cube-texture survival during deformation in a commercial-purity alloy, AA1050A (99.5% Al), where the effect is most clearly seen. As already discussed, this ability to survive the relatively high-temperature, slow-strain-rate deformation gives this texture component an advantage during recrystallization, allowing very high levels of the cube texture to be generated (figure 11). Once again, the information may be archived in this form, although, at present, the functional relationships do not reveal any clue to the fundamental mechanisms involved and further work is clearly needed to resolve these.

(*c*) *Formulation of working hypotheses for hot rolling of aluminium*

The mechanism of PSN has been described in great detail (see, for example, Humphreys & Kalu 1987; Humphreys & Ardakani 1994) and will not be discussed further in this paper. Of interest, however, is that the origins of this mechanism of recrystallization nucleation stem from fundamental studies on two-phase model systems (Humphreys 1979), seemingly far away from the present field of study.

Cube-texture survival and growth during annealing are more recent developments and worthy of further discussion. Originally observed in commercially hot-rolled aluminium (Weiland & Hirsch 1991), it is now linked to the fundamental studies on aluminium single crystals (Maurice & Driver 1993), which have highlighted the possibility of non-octahedral slip occurring in aluminium alloys under certain deformation conditions and strain paths. This working hypothesis was initially met with much healthy scepticism, but it is now more widely recognized that slip on systems other than {111} ⟨110⟩ may indeed be possible and, clearly, slip on {110} ⟨110⟩ would obviously allow the survival of cube textures in plane-strain or uniaxial compression. This condition alone may not be sufficient for the growth of this texture component during annealing, and some studies (Bolingbroke *et al*. 1994) have indicated the need for significant volume fractions of the 'S'-texture component, along with the cube texture that survives deformation, in order to develop large amounts of cube texture in the recrystallized state. The explanation behind this observation may lie in the need for more mobile grain boundaries, which may separate the S and cube textures to allow growth of the cube, but more work is needed to resolve many of these issues. Nevertheless, it would appear that the working hypothesis of non-octahedral slip is now almost fully integrated into the thinking of many scientists involved in this field of research.

(*d*) *Development of physically based models for hot rolling of aluminium*

If the same two examples of PSN and non-octahedral slip are followed through into the development of physical models for the development of texture during hot rolling and annealing of aluminium, it becomes clear that these really are state-of-the-art developments, and little exists as real evidence of physically based models. PSN has been modelled as a deformation event (Rabet *et al*. 1996) by considering the textures developed by a matrix deforming around a non-deformable particle, and under conditions where PSN is thought to dominate these textures have been used to predict the final texture in the product after annealing (Rabet *et al*. 1996). Similarly, crystal plasticity models have been used to incorporate non-octahedral slip, and with assumptions made as to the relative efficiency of slip on various systems (including octahedral slip) reasonable success has been achieved at predicting the survival of the cube-texture component after plane-strain compression deformation (Maurice & Driver 1996). Clearly, there is much work to be done in order to develop these working hypotheses into full predictable, physically based models, but the encouraging feature of these examples is the willingness of industry and academia to work collaboratively to solve these important issues.

6. Discussion and conclusions

Throughout this paper, a structure has been placed around the development of scientific understanding about one particular aspect of aluminium metallurgy: texture development in hot rolling. It should not be thought that this is a rigid structure, nor that it is new: it reflects how applied science evolves in many disciplines. But neither should it be ignored. If a fully predictive model of all aspects of hot rolling aluminium were required, including texture development, we have seen how two working hypotheses have been developed, and are being incorporated into models today, that explain some of the experimental observations described in this paper. However, there are many more to be discovered. Much more is needed for understanding the nature of the deformed state, under different conditions of strain, strain rate, temperature and time before we can appreciate enough working hypotheses to consider building a realistic model. To ignore this need puts resources into developing 'models' that will never predict correctly, because the physics of the actual processes is not included (because it is not known), rather than into developing the knowledge of the physics of the process from which models can be developed. This is obviously a task for collaboration between industry and academia, but the signs are encouraging and the funding bodies are now recognizing the need for this support for traditional industry.

No attempt has been made to place a value on the various stages of knowledge development, as described in this paper. The lack of understanding that may be associated with physical simulation of a process in no way undermines the value of the information developed. Likewise, the development of functional relationships to archive the information allows knowledge in this field to be quickly assimilated and the topic progressed. All the information derived at all levels of the hierarchy described above is of enormous importance in developing process windows for the development of products. To summarize, all the types of models described here are needed by the aluminium industry today for the successful continuation of the industry.

Finally, the issue of timeliness of information must be reinforced. Good, predictable information is required by industry to affect changes in process or new product development, as has been discussed throughout this paper. With the present state of modelling of the development of microstructure and properties from composition and processing, it must be recognized that this remains a vision. In many instances, physical simulation is the only predictive capability able to deliver the information required in the time-scale available, which is, in itself, a reflection on the developing nature of the scientific base in many applied disciplines. Functional relationships, as defined in this paper, between chemistry or process and characteristics or properties, represent the practical limit for most industrially based research. Close liaison with academia to allow the continuing development of working hypotheses, and, ultimately, physically based models, presents an enormous opportunity for this partnership to develop the scientific base on which future industry will depend.

This paper would be incomplete without the acknowledgement of the many colleagues in Alcan's research laboratories in England and Canada with whom many refreshing discussions have led to the philosophy adopted within this paper, and which has been practised during the author's career within Alcan. Thanks in particular go to Dr Stuart MacEwen for helping to organize these thoughts in a very busy climate, and to the many colleagues in academia who have helped, and are still helping, to further the knowledge base in aluminium materials science.

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Discussion

A. Howe (*British Steel plc, Swinden Technology Centre, UK*). The modeller has to know what he/she is supposed to predict. ‘Runability’ was mentioned as an important ‘property’, but what is the actual property which has to be predicted (and controlled) for this?

R. A. Ricks. ‘Runability’ is a loosely defined term intended to convey the ability of the rolled strip to run in continuous, or semi-continuous, operations such as beverage-can manufacturing. It may not be directly related to any simple mechanical property measured of the strip, nor to any known characteristic of the material, and it is only measurable when the strip enters production. It is, however, a reason to scrap the coil if the material fails to run on the line at the required levels of productivity.

L. M. Brown (*Cavendish Laboratories, University of Cambridge, UK*). Regarding models, I do not believe that atomistic modelling or even defect modelling will ever be useful as a directly predictive route to the properties of engineering structures. The computing times required exceed useful bounds—even if the density of memory and the speed of computing increase indefinitely at the present rate. For example, if the length of dislocation in the engineering product is one light year (as we have heard, and is true), then the fastest optical computing based on several iterations of structure must take many years to produce a complete model. What universities and atomistic models can provide is insight and students with insight who can hopefully inform the engineering models which ultimately must satisfy customers, legal requirements, etc.

J. H. Beynon (*Department of Mechanical Engineering, University of Sheffield, UK*). Dr Ricks showed very good comparison between the texture produced on a three-stand hot rolling tandem and the laboratory simulation using plane-strain compression testing. However, there is one difference in the modes of deformation in that in rolling the surface undergoes reversal of shear, whereas in plane-strain compression testing the shear is unidirectional. Does the good comparison mean that deformation texture evolution is independent of strain path?

R. A. Ricks. The compared values of volume fraction of texture components were measured at the mid-thickness point of both the rolled sample and the sample deformed by plane-strain compression, thus eliminating the difference in deformation due to the redundant shear strains associated with the rolling process. We have never tried to use plane-strain compression testing to simulate anything other than mid-thickness textures on the assumption that the variation in strain path would lead to poor texture prediction. The data do not indicate that deformation, or annealing, texture evolution is independent of strain path and in our experience this is most certainly not the case.

N. Hansen (*Materials Research Department, Risø National Laboratory, Roskilde, Denmark*). Dr Ricks mentioned that atomistic modelling and dislocation modelling are very far away when it comes to process modelling. I agree if he means modelling not the behaviour of many individual dislocation collisions. However, as dislocations assemble into groups, a gamma-fibre description of the parameters characterizing these groups will be sufficient to devise the needed structure–property relationships.

R. A. Ricks. I agree that when defining the basic building blocks of a microstructural model to describe the structure–property relationships, and the chemistry–process–structure relationships, more consideration should be given to the fundamental characteristics of the material to be modelled. Thus for aluminium, the high stacking fault energy means that the smallest microstructural feature needed to tackle the majority of problems will be the dislocation cell, rather than dislocations or atoms. As has already been mentioned, this will make the problem tractable, and models using cell networks have already been built. These assumptions about what are the the smallest components a model is built around may well be materials specific.