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Material Transition by Friction Induced and Continuous Solid-State Recycling of Aluminum Scrap

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Abstract. The utilisation of friction-induced solid-state recycling, methodically adapted to the CoNform process, facilitates the continuous production of semi-finished products. The material intended for recycling is conveyed continuously via a rotating wheel. The volume flow is influenced by fixed surfaces, deflections, and constrictions, thereby creating an asymmetrical flow profile. In order to effect a change in the mechanical properties of the semi-finished product, the material fed into the process can be modified. This enables the amalgamation of two alloys or the direct transition between them. The inhomogeneous flow conditions present within the tool give rise to the mixing of materials, thereby creating a graded multi-material zone. The multi-material zone was divided into different areas and traced back to the process conditions. Within the transitions, the connections between the alloys were examined, as well as the influence on the boundary layer. Material properties were determined for the individual areas and located along the length of the profile.

Introduction

In order to produce sustainable products, it is imperative to consider the entire product cycle and product design. Key aspects include minimizing energy consumption and resource-saving approaches [1]. Recycling of aluminum, in particular, has been demonstrated to offer significant savings potential and the potential for a circular economy. The fact that solid-state recycling does not involve melting of the raw material opens up new possibilities. These processes form press-welded bonds between the parts. The scrap is plastically deformed so that the insulating oxide layers on the surface break up and the bare aluminum surfaces can bond under pressure [2]. These bonds form at a lower energy level than conventional melting of the material. Energy analyses show that solid-state recycling of aluminum has the potential to save energy up to 90% compared to melting [3]. In addition, waste products such as toxic salt slag are eliminated, enabling waste-free recycling. Processing steps required to remove these side products are no longer necessary [4].

Maintaining the metallic bond in the crystalline structure enables new approaches because different phases can coexist. [5]. This phenomenon allows the targeted adjustment of material properties by mixing different alloys without having to specifically measure and balance the chemical composition [6]. Based on the initial strength of the materials to be mixed, a mass ratio can be determined by interpolation, which can be used to achieve individual strengths. On the other hand, foreign objects are also embedded in the structure. This can lead to defects that weaken the structure of the recycled component [7]. Consequently, particularly high demands must be placed on the purity of the starting material.

In lightweight construction in particular, the combination of different materials is specifically used to provide a customized structure for different load ranges. Such combinations not only reduce emissions during production, but also throughout the entire product cycle of the component. A prominent illustration is found in the field of lightweight construction, where the utilization of diverse materials is employed to counteract the effects of stress variations [1]. For dissimilar materials, an auxiliary joining element is mostly necessary, as material cohesion is often not possible. In these cases, overlaps are often necessary and the flow of force is directed to local areas by the auxiliary joining element [8]. If the materials of the elements to be joined are similar, in many cases it is possible to join the components by means of material bonding in a single joining step [9]. With the objective of reducing the number of manufacturing steps, efforts are being made to integrate the joining step directly into the shaping process for similar structures. Initial investigations have been conducted in solid-state recycling with targeted spatial arrangement of the chips to produce components with alloy transitions [10]. The investigations show that the process geometry like rejuvenation and temperature have an influence on product that needs to be investigated in detail. In addition, critical zones arise in the transition area of two materials where the process parameters need to be adjusted.

Another conceivable scenario is to change alloys during continuous processes. In this case, the old material is transported out of the system by the new material. This avoids long interruptions during which the machine has to be cleaned. Changes in the ongoing process are therefore particularly interesting when only small quantities are required, such as for special alloys or special profile shapes [11]. In the transition area, there is a zone where the two alloys mix to a multi-material zone. In these Muli-material zones, the material properties are not precisely defined and are therefore not suitable for special applications. Here, the geometry and kinetics of the process have a particular influence that must be taken into account in order to estimate the length of this zone [12].

This emphasizes the importance of considering material transitions to adapt the properties of the component as early as possible in the process. Integrating specific alloy changes can eliminate subsequent joining steps and reduce process times. Thoroughly assessing the alloy change during the ongoing process minimizes setup times and heating phases. Thus, comprehensive knowledge of alloy changes within the process enables efficient and sustainable design. This paper examines the transitions between two alloys during friction-induced recycling to identify the factors that influence them and their properties. This will enable a better evaluation of material transitions in continuous processes.

Methods and Materials

Friction-induced recycling, shown in Figure 1, is a continuous process that has been methodically adapted from the CoNform process. In this process, aluminum chips are fed evenly into the process over the groove of a rotating wheel from a temporary storage box via a conveyor. The wheel rotates at 11 revolutions per minute, powered by an electric motor. Friction between the groove in the wheel and the chips creates the necessary pressure for the process and transports the material forward. A tool insert continuously narrows the groove by compacting and shearing the chips. After further transport of the material by 90°, the material is dammed up and redirected into the horizontal plane. The pressure generated by friction forces pushes the material through a shaping die with a diameter of 5 mm. Turbulence and uneven flow are present within the tools. This results due to friction and deflection of the tools. The energy applied to the mass flow via friction counteracts the deformation of the material and the friction encountered on other tool surfaces. The mechanisms in the channel can be divided into three zones. First, the chips accumulate in the filling zone. They have not changed since their initial state and are not yet bonded to each other. This is the area where the gray aluminum connects with the wheel. The friction on the wheel transfers them to the yellow/orange gripping zone, where they are plasticized and compressed. In the last zone, the flow zone shown in red, the material is compacted to such an extent that there are no more air inclusions. In this zone, the material is largely homogenized. After the deflection, the channel is narrowed once again before the shaping die. The walls of this die also have retarding friction conditions, which means that not only the shape but also the channel length is an important influencing factor. Among other things, the pressure in the system and the temperature can be influenced. For the material flow it means, that this creates a leading core in the middle of the cross-section, which is slightly shifted upwards due to the deflection in the die-transition.

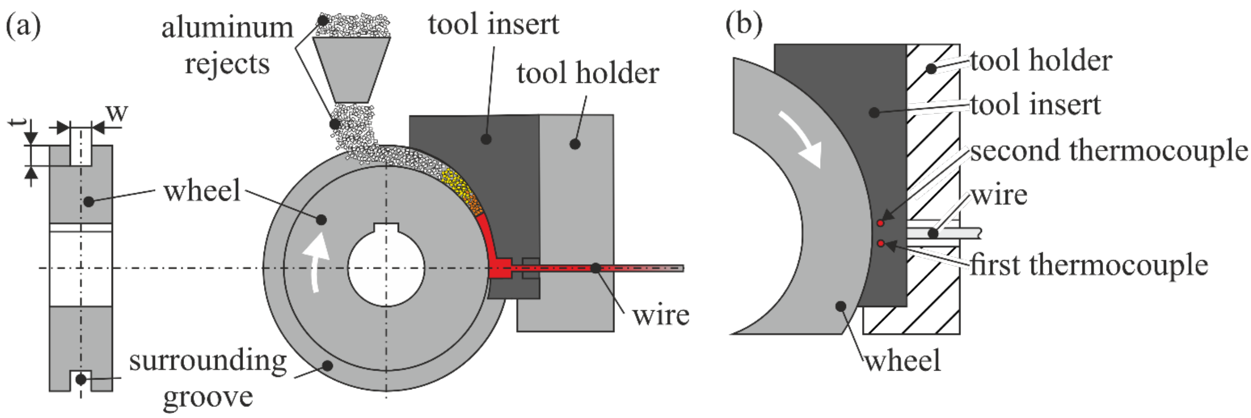


Fig. 1. Test setup for friction-induced recycling in two views. a) Left view: longitudinal section across the groove base area; right view: cross-section showing the groove narrowing and material flow. b) View of the tool with temperature measurement points.

A groove with a depth of t = 10 mm and a width of w = 12 mm is cut into the wheel. This is the initial cross-section into which the scrap is fed. The chips are narrowed to a gap of 4 mm using the tool insert. Dry milled chips of EN AW-6060 and EN AW-7075 alloys were processed. The geometric dimensions and bulk density of the chips are listed in Table 1. Between transitions, a filling of the intermediate container with a volume of 880 cm³ was processed. After a starting phase, the alloys were fed in alternated eight times under stable process conditions.

Table 1. Dimensions of the aluminum chips used.

Chip	length [mm]	width [mm]	thickness [mm]	Bulk density [g/cm^3]
EN AW-6060	1.9 ± 0.69	1.44 ± 0.25	0.14 ± 0.05	0.38 ± 0.01
EN AW-7075	4.04 ± 0.66	1.67 ± 0.24	0.04 ± 0.01	0.13 ± 0.01

During the process, the temperature is recorded tactilely at two points on the tool insert. The measurement is carried out using a K-type thermocouple (G/G-24KK-IEC) from Therma Thermofühler GmbH, Lindlar in Germany. A tensile-compression testing machine Z100 from Zwick-Roell GmbH & Co. KG, Ulm in Germany is used to determine the tensile strength. The test is carried out in accordance with DIN 50125 using form F. The hardness test was carried out using a NEXUS 4000 from INNOVATEST Europe BV in Maastricht, the Netherlands. The test was performed according to DIN EN ISO 6507 using the Vickers method with a test force of 3,942 N (HV0.3). The micrographs of the samples are etched with an electrolyte A2 for 100 s at a voltage of 20 V with the LectroPol-5 Polishing Unit electropolishing device from Struers, Copenhagen in Denmark. Grain sizes were evaluated in accordance with DIN EN ISO 643. The grain image is viewed on a Smartzoom 5 from the manufacturer Carl Zeiss IQS Deutschland GmbH, Oberkochen in Germany. Under this, the texture of polished samples was recorded across the longitudinal cross-section. The different alloy components could be evaluated using different gray scales.

Results and Discussion

The multi-material zones can be divided into different characteristic areas based on the change in the alloys added. From the moment a new alloy is added to the system, there is initially one area consisting of the pure predecessor alloy (area 1 in Figure 2). After this, the new alloy is initially added in small quantities in the middle. This is followed by a broadly multi-material area in which both alloys are present in high proportions (area 2). Before the new alloy is present in its pure form, there is another area in which larger volumes of the predecessor alloy occur in sections (area 3). These are attached to the tool and thus indicate the end of the multi-material zone. Based on this multi-material, the general mass flow in friction-induced recycling is also directly visible. In a thin outer layer, feedstock is retained over a longer distance by high friction on the shaping die surface. In addition, there is a parabolic distribution, which is shifted upwards by the deflection of the mass flow. This means that the new material flows into the upper part of the strand more quickly. The greatest distance is travelled in the area where the flow is deflected over the outer curve. This leads to high frictional resistance and, consequently, a slow flow velocity.

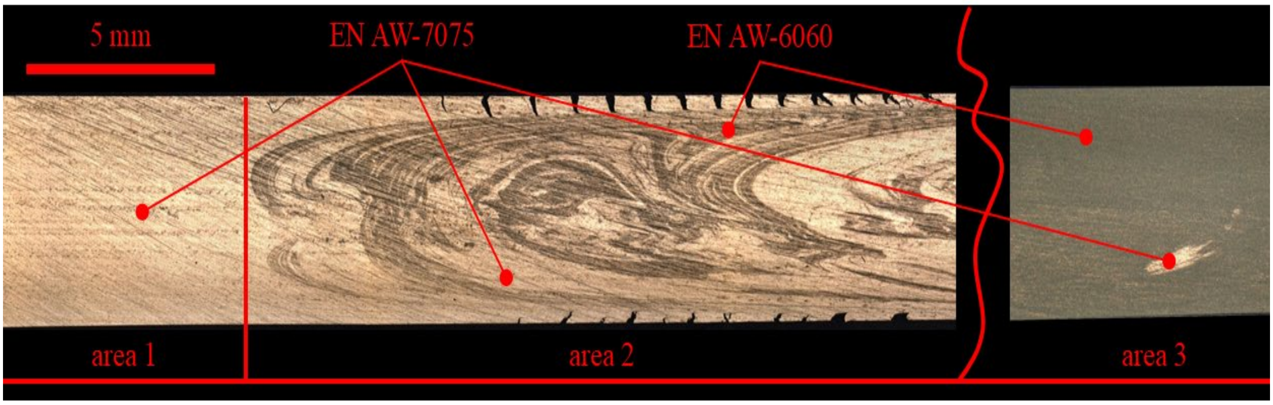


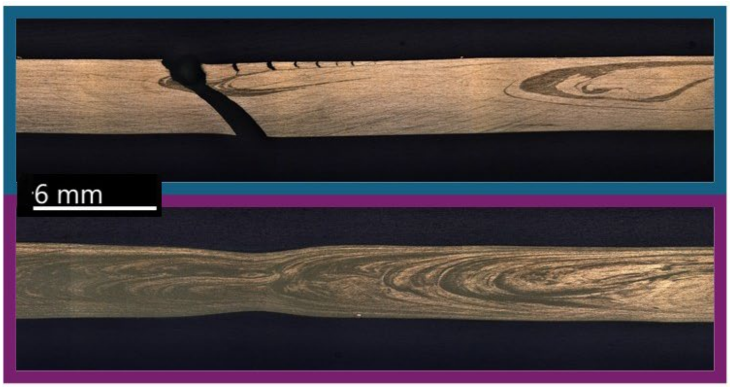
Fig. 2. Longitudinal section of a profile from the transition from EN AW-7075 (left) to EN AW-6060, classified into three proportions of alloy mixtures. area 1) pure predecessor alloy. area 2) high multi-material area of the two alloys. area 3) with small admixture of the previous alloy.

In production, there are no significant differences in the process parameters for the alloys processed. The temperature when processing the multi-material zones from EN AW-7075 to EN AW-6060 is around 440 °C. During manual alloy changes, when the new alloy is poured into the crucible, the temperature drops briefly (~20 K) and then rises again to the process temperature when the next alloy is added. When changing alloys, a mark was made at the die exit from which the position in the profile at the time of the change can be determined. With the material in the die and the material in the wheel groove, a short section with the old material is still conveyed after the change until the first admixtures of the new material are present in the middle of the profile. Table 2 shows that this area has the lowest standard deviation in comparison to all multi-material areas. Based on this length, indirect conclusions can be drawn about the zones in contact with the wheel. The largest area is measured with the last one. In addition, not only the largest standard deviation is considered here, but also the most irregular structure. This results in an inhomogeneous length of approx. 168 mm, which is calculated from the difference between the minimum and maximum values of the first area added to the maximum values from areas two and three.

Table 2. Statistical lengths of the individual areas in the multi-material over eight material alternations.

	area 1	area 2	area 3
mean [mm]	26.4	45.4	79.5
max. [mm]	32	55	103
min. [mm]	22	32.7	45.6
standard deviation [mm]	3.5	7.9	30.1

In the area 2 of the multi-material zones, there are high changes of alloy section length. In the middle of the profile, the thickness of the sections is in the range of a few tenths of a millimeter and is stretched towards the edge to a thickness of one hundredth of a millimeter. Area three is characterized by thicker admixtures with dimensions in the millimeter range, which thin out towards the edge. In the edge layers, which extend over large parts of the second area due to the friction conditions, a distinction must be made between the alloys. The softer EN AW-6060 can be thinned out considerably, with the thickness decreasing to 80 µm. A thicker edge layer forms with EN AW-7075, which is almost constant at 0.3 mm.
When switching from EN AW-7075 with high strength to EN AW-6060 with lower strength, tearing in the surface of the edge layer can be observed. This is due to different flow behavior, which can lead to material failure at the end of the tool. At the tool contact point, friction generates high shear stresses, which slow material flow. If softer material components are present in the layers near the edge, the harder components shear them more intensely due to the faster flowing core. This leads to additional stresses besides surface friction due to the structural ductility of the edge layers. Consequently, higher stresses arise locally due to velocity differences than in a homogeneous case. To mitigate this effect, it is conceivable to create transitions that are deliberately drawn out longer by making the change gradual rather than abrupt, with mixed chips. If the transition is reversed, the difference in flow behavior is not critical for the softer EN AW-6060 material. Tensile tests show that stress peaks can form at locations with surface defects in the presence of small amounts of EN AW-6060. This can lead to premature failure. Significantly restrict the plastic behavior of the material. An example of this is shown in Figure 3, where failure occurs up to 50% earlier and without necking. However, in general, failure can be observed in areas with low strength. Despite different local material properties and thus interfacial stresses, the areas with the multi-material do not represent a particular weak point. In terms of flow behavior, the multi-material results in a gradient that depends on the mass fractions. It can be seen that in areas where there is no significant mixing, larger proportions of the stronger alloy (EN AW-7075) take on a load-bearing role and weak points form where failure occurs. These areas, which are much softer locally, cannot be calculated precisely.



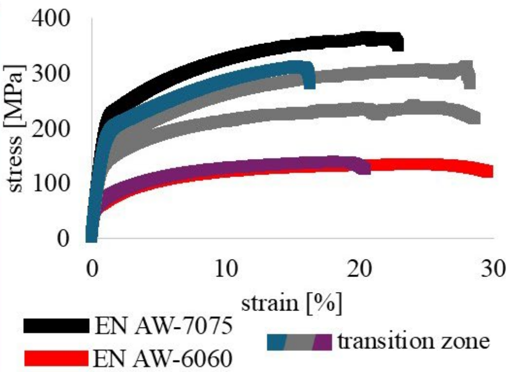


Fig. 3. left) Longitudinal section of tensile test specimens outlined with legend color; top: Premature failure due to defects in the outer surface and the initial addition of EN AW-6060 to the EN AW-7075 base alloy; bottom: Necking before a larger addition of EN AW-7075 as a stiffer alloy. right) Stress curves in the multi-material zone in the area between the pure alloys.

Significant differences are apparent in the hardness measurement. In areas with a large number of fine transitions, the average hardness is 59 ± 12.5 HV 0.3. Similar to tensile strength, a mixed value of the two basic strengths is evident here, with a high degree of variability, as shown in Figure 4. In the pure EN AW-7075 area, a hardness of 86 ±1.2 HV 0.3 was measured, and in the EN AW-6060 areas, 39 ± 1.8 HV 0.3. As the multi-material zone progresses, the dispersion of the hardness values decreases and the values approach the hardness of the pure alloy. However, there are significant large local outliers in the admixed material. Individual points that do not tend toward a pure alloy are located in areas of transition with different alloy layers. In these areas, adjacent alloy layers provide support by bearing part of the load.

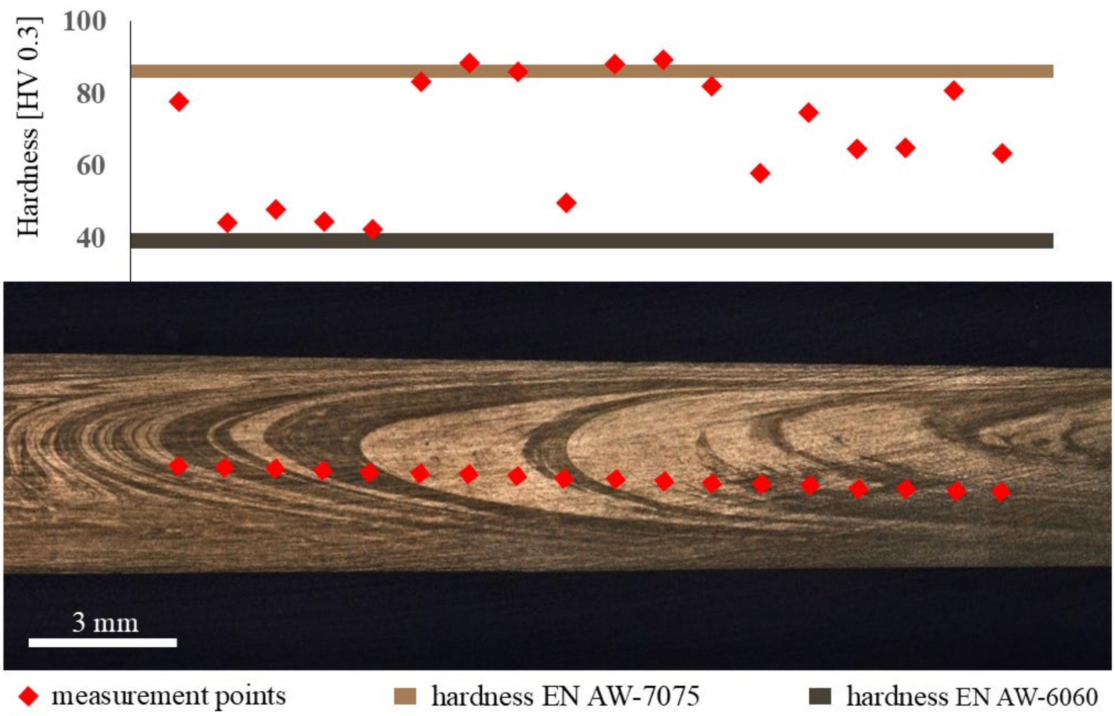


Fig. 4. Measured hardness with assignment to profile position, high proportion of alloy on the left side, the right-hand measuring points are in an area with mixed material properties Alloys.

Mean grain diameters were calculated to indirectly evaluate the deformation ratio of the different alloys interacting with each other. In the pure alloy ranges, the mean grain diameter was determined to be 4 µm for the harder alloy EN AW-7075 and 11 µm for the softer alloy EN AW-6060. When different alloy proportions are present side by side in the strand, the grain sizes change depending on the ratio of the alloy. In this combination, the softer alloy, EN AW-6060, will undergo greater plastic distortion, while the stronger alloy, EN AW-7075, will undergo lower elongation when pushed through. Thus, the mean grain diameter of EN AW-7075 can increase to 16 µm in areas with a high proportion of alloy change, while the mean grain diameter of EN AW-6060 decreases to 6 µm at this ratio. The greatest grain refinement occurs when EN AW-6060 is surrounded by a high proportion of EN AW-7075. In this case, the grain size of EN AW-6060 decreases by 4 µm compared to EN AW-7075, which has a grain size of 8 µm. Area three, where only individual particles of the other alloy are mixed into the strand, must be evaluated separately. These admixtures, shown in Figure 5 on the right, detach from the tool contact and are exposed to high shear forces due to surface friction. This results in grain refinement. Consequently, even when the solid alloy EN AW-7075 is embedded in the softer EN AW-6060, the mean grain diameter can be as small as 5 µm.

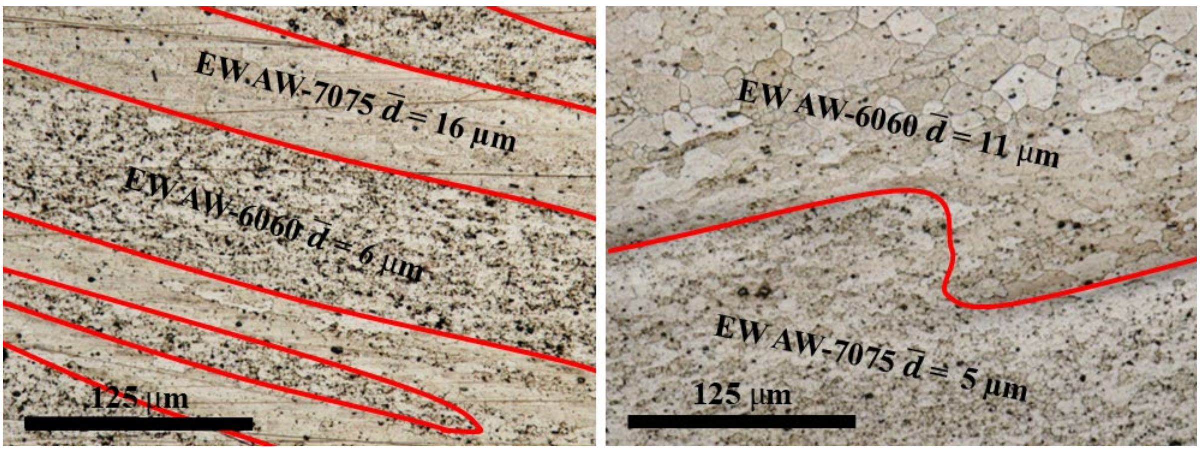


Fig. 5. Left) Microstructure of area 2 in a transition from EW AW-6060 to EN AW-7075 with a high alloy content change. right) AW-7075 piece embedded in EN AW-6060 in area 3.

The multi-material zone is an extremely complex area dependent on base materials and their mixtures. Approximately predicting these based on process conditions allows one to draw conclusions about material quality.

Summary

The investigations show that alloy changes are possible during the running process in friction-induced recycling. The resulting multi-material area can be divided into three areas from the moment another alloy is added to the plant. First, a short piece of the old pure alloy is extruded. This is followed by a section in which the alloys are finely distributed. The third stage is characterized by local admixtures of the old alloy. Defects occurred in the cladding area during the transition from the harder EN AW-7075 to the softer EN AW-6060 alloy. This is due to high material stress caused by surface friction and additional stress differences resulting from an inhomogeneous alloy distribution. The process management must be adjusted to prevent critical shifts. The strengths in finely mixed areas result from a ratio of the two starting materials. In larger areas of an alloy, its properties are dominant. The elongation of the material depends on the strength ratio of the alloys. The stronger alloy shears the softer alloy more strongly during the flow process. This results in increased grain refinement in the soft areas. In contrast, the harder alloy deforms to a lesser extent, resulting in a coarser grain structure. These visible flow differences confirm the stress differences in the boundary layers and demonstrate the significant influence of the alloy ratio on inhomogeneous structure formation and system strength.

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