

Article

Semi-Solid Slurries for Rheocasting of Hypoeutectic Al-Si-X Alloys Produced by Self-Stirring in Serpentine Channels

Hernández Alfredo ^{1,2,*}, Chávez José Federico ¹, Hernández Aldo ³ and Suárez Miguel Ángel ⁴

¹ Department of Engineering in Metallurgy and Materials, ESIQIE, Instituto Politécnico Nacional, UPALM, Mexico City 07738, Mexico; jfchavez@ipn.mx

² Department of Materials Engineering, Tecnológico de Estudios Superiores de Coacalco, Coacalco 55710, Mexico

³ Department of Mechatronics Engineering, Universidad Politécnica del Valle de México, Tultitlán 54910, Mexico; aldo.hernandez.ramirez@upvm.edu.mx

⁴ Department of Materials, Azcapotzalco, Universidad Autónoma Metropolitana, Mexico City 02128, Mexico; masuarez@azc.uam.mx

* Correspondence: ahernandezh@ipn.mx

Abstract: Nowadays it is common to see the production of complex and critical automotive and aeronautical components reduced in weight for energy efficiency using light alloys with improved microstructural and mechanical properties. The casting processes involved in this trend are strong; in this study, an optimized design of a vertical serpentine channel and a novel design of a horizontal serpentine channel to produce semi-solid slurry (S2S) with thixotropic behavior by self-stirring for rheocasting of A380 and A356 alloys are tested. Simultaneously, chilling during solidification, flow development, and shearing on the alloys to improve the performance of solid fractions and self-stirring at high shear rate are applied. The effects of these conditions on the modification of the morphology transition of the $\alpha(\text{Al})$ phase from dendrite to equiaxed grain are discussed. The results suggest the ability of the mentioned processes to promote the morphological transition of the primary solid due to the produced equiaxed grains of $\alpha(\text{Al})$ phase having sizes between 25–50 μm from A380 alloy processed by vertical self-stirring. On the other hand, the treatment of the A356 alloy using the new horizontal serpentine channel produces equiaxed grains with an average size of 39 μm . Unexpected Si crystals, trapped in the $\alpha(\text{Al})$ phase using both methods with both alloys, are detected. The applied operation parameters were aided by gravity-pouring close to the liquidus temperature, and the obtained microstructural results show the ability for S2S to form alongside thixotropic behavior and non-dendritic solidification by mean of self-stirring in the serpentine channels, suggesting the potential for further experiments under die-casting conditions.



Citation: Alfredo, H.; José Federico, C.; Aldo, H.; Miguel Ángel, S. Semi-Solid Slurries for Rheocasting of Hypoeutectic Al-Si-X Alloys Produced by Self-Stirring in Serpentine Channels. *Metals* **2024**, *14*, 413. <https://doi.org/10.3390/met14040413>

Academic Editors: Carlos Alexandre Dos Santos and Eleani Maria Da Costa

Received: 29 February 2024

Revised: 25 March 2024

Accepted: 25 March 2024

Published: 30 March 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: casting; rheocasting; solidification; microstructure; characterization

1. Introduction

Semi-solid processing (S2P) was introduced 50 years ago by MIT researchers; the rheological behavior, including the decrease in viscosity of Pb15Sn alloy, was published by Spencer et al. [1]. The concept of dendritic structure transformation during solidification was proposed by Flemings; since then, understanding of the microstructural change to the shape of the primary solid from dendrite to sphere by shearing, which produces a significant decrease in shear stress and viscosity, has been attained. This behavior, identified as thixotropy, is common in ceramics and polymers, but until now unknown in metallic systems [2,3].

The S2P technology made available in the last 35 years has created a new trend in near-net shape manufacturing, in the form of casting light alloys with enhanced microstructural and mechanical properties. Most critical and complex aeronautical and automotive components are conventionally processed by die-casting and further heat treatments to

produce dendritic solidification followed by quenching, aging, and spheroidization to obtain the final microstructure at a low cost.

In conventional die-casting of hypoeutectic Al-Si-X alloys, the melt is injected into the mold, then solidification begins, since the filled mold, the stationary liquid alloy, and the as-cast microstructure are in a dendritic $\alpha(\text{Al})$ phase surrounded by an Al-Si eutectic; in rheocasting, on the other hand, a controllable slurry or mush state containing the non-dendritic primary solid within the liquid phase matrix is produced from the melt for further die-injection into the mold, and the equiaxed morphology of the solid $\alpha(\text{Al})$ phase directly in its as-cast condition is finally obtained due to dendrite trimming during the growth of the solid phase.

Strong agitation breaks up the dendrites, promoting the formation of new grains, since inserting the arms into the bulk improves the distribution of new globular particles; under this condition, the slurry viscosity decreases while shear rate increases because of the non-Newtonian behavior of the semi-solid alloy.

Recently, efforts have been focused on adding a rheocasting process to the die-casting industry [3]. Rheocasting is an S2P method that enables the alloy to transition from the liquid to a semi-solid state with thixotropy due to the increase of the solid phase with non-dendritic morphology by simultaneously solidifying it at controlled cooling rate and stirring it at high shear rate [4–9].

Due to the interest in this field, several rheocasting process are in the R&D stages, with researchers seeking a less complex formation route for slurries directly from melt with minimal investment in equipment and minimal modifications to the process. The processing energy saving, the reduction in cycle time, the decreased damage to dies, and minimal casting defects, such as porosity and shrinkage, allows for the most cost-effective process [2,10,11].

Unlike thixoforming, rheocasting does not requires special billets. The feedstock is the liquid alloy produced by one or another conventional melting method. The removed gating and risering systems, rejected parts, and scrap can be simply recycled in-plant, key reasons to choose S2S casting over conventional casting as a high quality and cost-effective process.

In comparison to high-pressure die-casting (HPDC), rheo-die-casting (RHDC) comes with advantages including improving microstructures, increasing mechanical properties, and decreasing defects in a cost-effective manner. The presence of pinhole/porosity in injected parts produced by HPDC is widely known, and the difficulty of the control process due to the cold chamber design and the operation parameters such as injection pressure and flow rate are responsible for flow turbulence and air entrapment to produce these typical defects. The sound production of parts, due to the better control of RHDC, is possible because the aspiration effect disappears and the flow turbulence is decreased.

The non-dendritic microstructure produced by S2P, which would increase the mechanical properties, the comparison of UTS, and strain for hypoeutectic Al-Si alloys produced by conventional casting and rheocasting, is reported on in Table 1. It can be noted that non-dendritic conditions increase the ductility of the alloy without being harmful to the tensile strength. The heat treatment T6 is defined by quenching and aging together. There are no data available for the non-dendritic A380 alloy.

Table 1. Mechanical properties of Al-Si alloys according to the casting method.

Alloy	Casting Process	Tensile Strength, (MPa)	Strain, (%)
A356	HPDC + T6	227	3
A356	RHDC	243	4
A356	RHDC + T6	277	14
A380	HPDC + T6	317	3

The performance of RHDC depends on the method used for S2S forming. In this study, two different melted light alloys were gravity-poured into two serpentine pouring channels to produce thixotropic S2S as potential feedstock for HPDC.

2. Recent Developments in Slurry Forming

According to Flemings [2], the slurry casting route is preferable via immediate industrial applications and potentially a route for further R&D. Initial attempts to bring a rheocasting process into the die-casting industry involved modifying the process, machines, and dies, including in some cases, significant investment in new equipment and shifts in technology; however, these are unacceptable ideas.

Those initial proposals have been refocused to highlight two ideas: the objective must be process improvement, not process change; and the concept must be shifted from how to where to produce slurry on demand. Thus, a different approach to S2S formation has been applied to produce the mushy state at a low formation temperature close to the liquidus, with control of the solid fraction for simplified pouring into a shot sleeve with minimal modifications to the process, die system, and equipment.

Several methods have been developed to prepare S2S directly from the melt; these include mechanical stirring, electro-magnetic stirring, gas bubble induction, and self-stirring by channel flow. Most of them involve high nucleation for enough solid particles to form by forced convection during solidification to cause dendrite trimming in the expected equiaxed structure in the $\alpha(\text{Al})$ phase [2]. A complex process window in each slurry formation must be expected due to a wide combination of process parameters such as viscosity; shear rate; solid fraction; cooling rate; shear time; forming temperature; alloy composition; solute distribution; and history of the melt treatment including degassing, grain refinement, and eutectic modification [12–16].

By mechanical stirring, the dynamics of the rheological treatment are commonly generated by mean of impellers or rods immersed inside the melt. The process has advanced from a batch method to a continuous slurry supply; however, this technique has found limited application on the industrial scale due to its drawbacks, such as erosion of the stirrer, contamination of the slurry by oxides and dross, gas entrapment, low productivity, and difficulty in process control [17–19]. This kind of method produces a typical grain size between 100 and 400 μm during the $\alpha(\text{Al})$ phase.

Electromagnetic stirring was developed to overcome the technical complications associated with mechanical stirring, including advantages in cost-effectiveness. In this method, a ceramic crucible contains the melt for refining treatment to produce abundant nuclei; in this state, the melt, which is close to the liquidus in temperature, is charged into an induction furnace to produce vigorous stirring for further formation of the product inside the die-casting machine. The shear is induced to the charged melt by an electromagnetic field acting on the increase of the solid fraction by the temperature decrease to obtain new fragmented and equiaxed crystals with a size normally about 30 μm .

The UBE process, also known as new rheocasting (NRC), includes electromagnetic stirring to produce slurry on demand. The combined stirring–cooling close to the liquidus temperature of an Al-Si-X alloy results in abundant nucleation of the primary $\alpha(\text{Al})$ particles in the slurry. Furthermore, these methods could have favorable effects on the formation of intermetallic particles, promoting precipitation hardness [20].

The gas-induced superheated slurry (GISS) method was introduced by Wannasin et al. [18,19]. A graphite diffuser is immersed into the melt just above its liquidus temperature to inject micro-sized inert gas bubbles under suitable conditions; chill and vigorous convection are achieved by the flow of the fine inert gas bubbles around the cold diffuser to produce grain refinement of a large number of fine solid particles with a non-dendritic structure surrounded by the remains of the melt. The slurry, with significantly lower heat content with respect to the melt and the controlled solid fraction, is then ready for die-casting, squeeze-casting, or gravity-casting [19]. More than 100 pieces of GISS equipment have been acquired by top companies around the world.

Considering the basic ideas of controlling nucleation and inhibiting dendrite growth, serpentine channel pouring (SCP) has been developed as a different method. The serpentine channel is contained within a heat conductor block. The melt is poured into the block, and simultaneously, solidification–stirring is performed inside the serpentine channel,

modifying the solid phase shape while the slurry, with its increasing solid fraction, is obtained. A slurry with the desired controlled solid fraction is the block output.

The SCP process has two advantages with respect to the above-mentioned processes. On one hand, the serpentine channels have strong heat transfer capacity enabling them to produce a chilling effect, which creates a heterogeneous nucleation substrate. The growth of the dendrites is effectively inhibited by the increase of the primary $\alpha(\text{Al})$ nuclei. On the other hand, the stirring occurs when the alloy slurry flows through the closed and curved serpentine channel, and the direction of the alloy slurry changes several times with the effects of gravity; in this way, the movement at decreased viscosity of the formed slurry has the function of self-stirring [21–23].

Zhi-Young Liu et al. recommended an increase to the curve number and decrease of the curve diameter to improve microstructural results; furthermore, the pouring temperature has an effect on grain size. The temperature gradient and the concentration gradient of the slurry state decrease in the serpentine channel by means of self-stirring [21]. Similar simplified methods for slurry formation have been developed, such as the cooling slope [24–26], the cooling channel [27], and the ultrasonic treatment (UST) [28].

3. Experimental Procedure

In this study, two SCP assemblies were designed and tested to produce S2S; two arrangements, optimized vertical SCP and a new horizontal form of SCP, with enough contact surface were created to produce chilling for abundantly nucleation and many bends for self-stirring at high shear rate to obtain a change from a dendrite to a globular shape in the primary solid, free of the agglomeration effect on the grains. The vertical design includes a rectangular cross-section on the channel, while circular transverse section was designed for the horizontal channel. In both cases, the treated S2S was discharged into a cast iron mold to produce a flat slab.

The solid fraction $f_{\alpha(\text{Al})}$ was calculated by the Scheil model [29–34] according to the Equations (1) and (2) in terms of the process temperature (T), and the solute distribution coefficient between the solid and the liquid phases (k), where T_m is the melting temperature of Al, T_l is the liquidus temperature of the alloy, and T_e is the eutectic temperature of the Al-Si system; the solute distribution coefficient for hypoeutectic Al-Si alloys is equal to 0.1309 just at the eutectic temperature. The boundary conditions for hypoeutectic Al-Si alloys are $T_e \leq T \leq T_l$ for the process temperature and $0 \leq X_0 \leq 0.126$ for the composition field, where X_0 is the alloy composition and X_L is the solute content at T into the liquid. Both data are reported in fractions by weight.

$$f_{\alpha(\text{Al})} = 1 - \left[\frac{T_m - T_l}{T_m - T} \right]^{\left(\frac{1}{1-k} \right)} = 1 - \left(\frac{X_0}{X_L} \right)^{\left(\frac{1}{1-k} \right)} \quad (1)$$

$$k = 0.1309 \frac{\left[1 - \exp\left(\frac{T_m - T}{T} \right) \right] \left[1 - \exp\left(\frac{T_e - T_m}{T} \right) \right]}{\left[1 - \exp\left(\frac{T - T_m}{T} \right) \right] \left[1 - \exp\left(\frac{T_m - T_e}{T} \right) \right]} \quad (2)$$

Two common hypoeutectic alloys of the Al-Si-X system were selected for the experimental tests for SCP self-stirring: A380 alloy (Al-Si-Cu) (Form Technologies, Charlotte, NC, USA), which is in wide use for block engines, and A356 alloy (Al-Si-Mg), extensively applied in wheels, two automotive components produced at high scale. The chemical compositions of the cited alloys determined by optical emission spectrometry are reported in Table 2.

Table 2. Chemical composition of alloys, % by weight.

	Si	Mg	Cu	Fe	Mn	Zn	Ni	Ti	Sr
A380	9.00	0.012	4.050	0.361	0.012	0.051	0.015	0.014	0.0001
A356	7.12	0.338	0.003	0.369	0.011	0.032	0.015	0.011	0.0001

The liquidus temperature of both alloys was determined to define the pouring temperature for rheocasting experiments close to the appearance of the $\alpha(\text{Al})$ phase. The samples were obtained from the ingots used as feedstock for melting. The liquidus temperatures tested by differential scanning calorimetry (DSC) are 585–595 °C for A380 alloy and 605–620 °C for A356 alloy, respectively, according to the tests run shown in Figure 1.

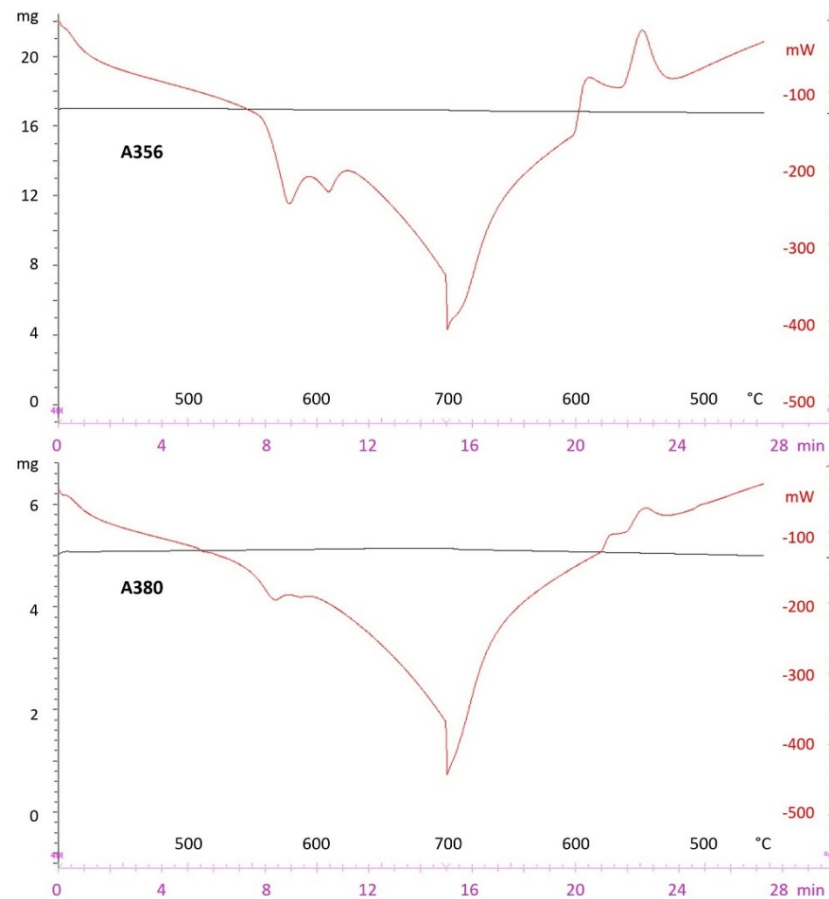


Figure 1. DSC tests carried out for samples of A380 and A356 alloys obtained from the feedstock (ingots).

The melts in weight of 420–460 g were placed in an electric furnace at 720–730 °C, degassed with C_2Cl_6 , refined with Al-5Ti-B, and modified with Al-10Sr to obtain 100 ppm of Sr. The master alloy Al-5Ti-B was added into the melt to promote the heterogeneous nucleation, refining in this way the size of the primary solid. The crystallographic structures of TiB_2 and Al_3Ti formed by the inoculant made it easier to increasing the number of nuclei in the poured liquid due to the coincidence of favorable crystallographic planes which were, on one hand, perpendicular to the $[111]$ growth direction and on the other hand, parallel to the $[\bar{1}10]$ and $[\bar{1}\bar{1}2]$ directions of the $\alpha(\text{Al})$ phase. The quantity of inner refining by the master alloy in addition to the provided outward by the channel for the chilling effect were the support for abundant nuclei, the experimental set-up was showed in Figure 2 and the mechanism for the morphological transition of the primary solid by chill and trimmed dendrites was proposed in Figure 3.

The Sr added by mean of the Al-10Sr master alloy is a modifying agent commonly used in Al-Si-X alloys to refine the eutectic structure because it depresses the needed temperature to 15 °C and then stabilizes the eutectic transformation temperature; under these conditions, the morphology of the eutectic silicon is changed from a fine flake shape to a refined fibrous shape. Additions of 100–150 ppm are suitable for this eutectic modification.

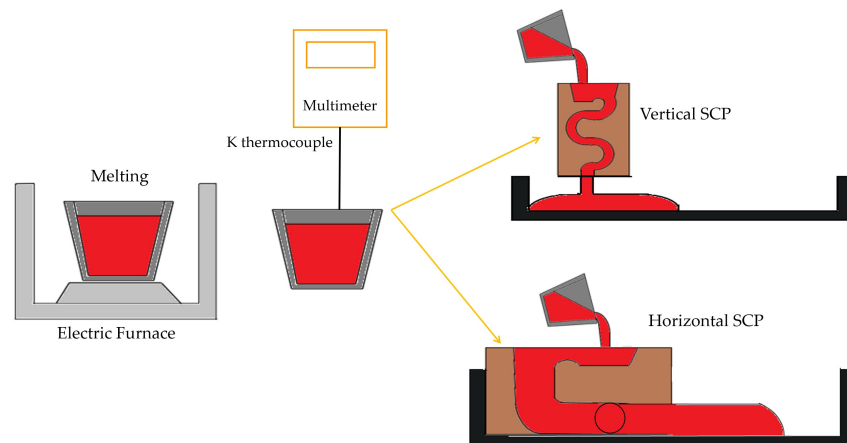


Figure 2. Schematic diagram of the vertical and the horizontal SCP processes.

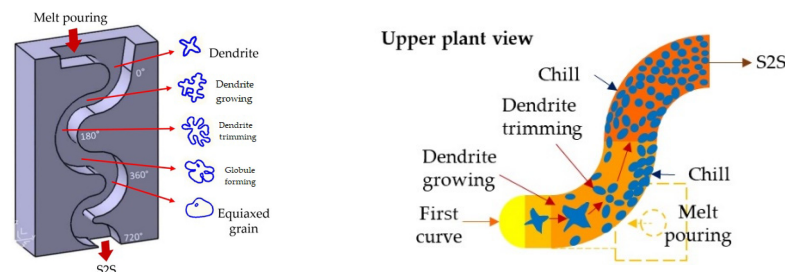


Figure 3. Schematic diagram of the microstructural evolution mechanism from dendrite to S2S with equiaxed grains in the $\alpha(\text{Al})$ phase in both vertical SCP and horizontal SCP.

The A380 and A356 alloys were processed by vertical SCP and horizontal SCP respectively, and in both cases the preheated at 200–220 °C serpentine channels were created in cooper blocks to obtain significant nucleation by chilling and self-stirring from the curve number and the curve diameter.

On one hand, the A380 alloy was gravity-poured into the vertical SCP shape at temperature between 605–610 °C. The measured cooling rate is 5.7–5.8 °C/s. The design of the vertical serpentine channel included four curves equivalent to 720° in rotation with a progressive reduction in the curve radii from 14 to 9 to 4.5 mm; the cross-section of 300 mm² remained constant along the channel. Solidified samples between 225–275 g in weight were produced.

Meanwhile, the A356 alloy was gravity-poured via horizontal SCP in a different design including three curves to produce 270° in rotation with 283.5 mm² of constant cross-section. For these experiments, the pouring temperature varied between 615 and 690 °C to modify the solid fraction. Solidified samples 205–240 g in weight were obtained.

The vertical and the horizontal serpentine channels, including their respective runner castings, are shown in Figure 4; the samples produced by the second method can be observed in Figure 5.

In this study, horizontal SCP is introduced as a new technique for S2S formation by self-stirring with advantages over vertical SCP. The flow trajectory changes from vertical to horizontal, thus decreasing the height of the liquid column to control the pressure and velocity during gravity-pouring; furthermore, the capacity for channel filling is improved, thus reducing the entrapment of air bubbles.

Other key benefits are the improvement of flow development and heat transfer by the use of a circular cross-section due to the rectangular cross-area along the channel, a shorter route with fewer curves has been included to increase yield by minimal consumption of the alloy in the channel; under these conditions, it is possible to obtain a semi-solid alloy further from the unloading gate despite the low pouring temperature.



Figure 4. A380 and A356 alloys rheocast by vertical SCP and horizontal SCP respectively.



Figure 5. Runner and samples of rheocast A356 from left to right at 615 °C, 630 °C, 630 °C and 690 °C, respectively, made using horizontal SCP.

The chilling process is not affected due to the adequate availability of contact surface area between the slurry and the wall of the channel; moreover, dendrite formation is inhibited by the large number of nuclei associated with the space reduction in the fluid.

The experimental assembly for tests by horizontal SCP is a simplified and compact device allowing for greater ease of execution and control of experiments, and the kit can be installed close to the furnace for fast testing. The container with the serpentine channel is a 125 × 75 × 75 mm cooper block put on top of the mold.

Microstructural characterization of the A380 alloy was carried out by OM and SEM on samples selected from two positions, at rotations of 360° (the middle of the route) and 720° (end of the vertical channel); on the other hand, the A356 samples were chosen at 270°, corresponding to the end of the horizontal channel. The samples for metallographic analysis were etched for 10 s by hydrofluoric acid at a concentration of 1 % by volume.

The globule size (G_{LS}) was determined using the direct measurement method, which consists of measuring the diameter of each of the globules in the micrograph. The shape factor ($C = 1 \therefore sphere ; C \rightarrow 1 \therefore needle$) was calculated using the following expression: $C = \frac{(4\pi A)}{P^2}$, where A is the area of the globule and P is the perimeter [35].

These microstructural parameters were measured with the software program Image J (<https://imagej.net/ij/>, accessed on 24 March 2024), and at least 30 measurements were taken to obtain average values.

4. Results and Discussion

4.1. A380 Alloy Processed by Vertical SCP

The metallographic analysis by optical microscopy and SEM in Figure 6 shows the morphological transition to equiaxed grain in the $\alpha(Al)$ phase. The selected regions of the vertical serpentine channel to be analyzed were at the middle and at the end of the route;

halfway along the channel, globular $\alpha(\text{Al})$ phase in the 25–100 μm size range was produced, while at the end of the channel, particles in order of 25–50 μm were obtained. In both cases it is evident the absence of dendrites; however, some clusters or agglomerated globules were detected.

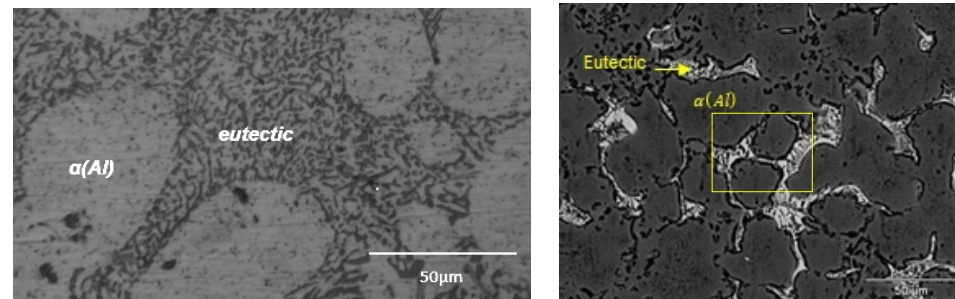


Figure 6. Non-dendritic A380 alloy produced by self-stirring through vertical SCP at rotations of 360° (middle of the route) and 720° (end of the route).

Several stains inside the $\alpha(\text{Al})$ phase were observed by optical microscopy; a detailed analysis of the globules by SEM showed the presence of entrapped Si crystals within the primary solid due to the saturation of solute in the solid phase by its limited solubility. Furthermore, the rejection and diffusion of Si outside of the grain was inhibited by rapid solidification.

Linear EDS was carried out to identify the compositional changes in the primary solid and the eutectic structure. The enlarged region in Figure 6 was analyzed according to the trajectory showed in Figure 7; in this case, the primary solid is the spheroidal $\alpha(\text{Al})$ phase with a rich content of Al containing dissolved Si and Cu. The detected stain at the middle of this grain is a retained Si crystal supported by the decrease in Al and the increase in Si content; from this point, the EDS test reports symmetrical behavior in the composition profile. The eutectic structure around the equiaxed crystals of the $\alpha(\text{Al})$ phase was formed from the remains of the liquid enriched in Si and Cu and alternating fibers of eutectic Al-Si, and some Cu_2Al precipitates are observed in this zone.

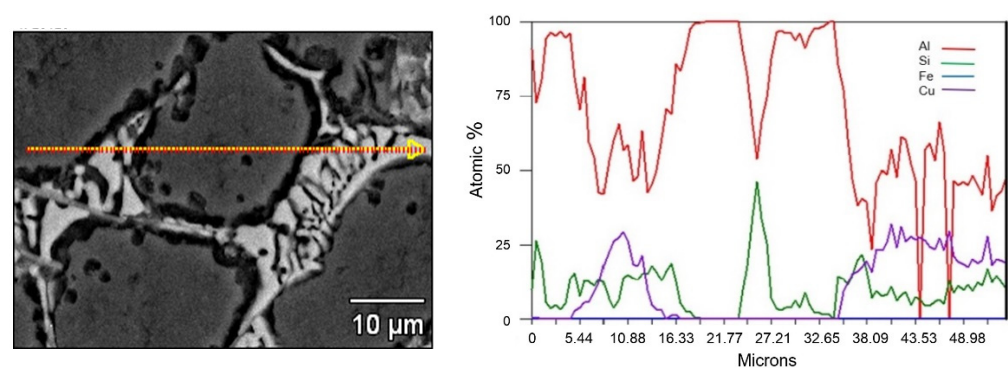


Figure 7. EDS linear scanning of the highlighted region in the previous micrograph including the eutectic structure around the equiaxed grain of the $\alpha(\text{Al})$ phase in A380 alloy.

The EDS mapping in Figure 8 shows the compositional field on the equiaxed particles of the $\alpha(\text{Al})$ phase with average size on 30 μm surrounded by a Si-enriched eutectic structure. The results of the SEM and EDS tests coincide in the presence of Si crystals entrapped in the $\alpha(\text{Al})$ phase due to the saturation of solute of the primary solid, low diffusion, and the chilling effect.

The A380 alloy is difficult to treat by semi-solid processing due to its short temperature interval in the mushy state and the fact that the top of solid fraction available for the treatment is 0.33 at eutectic temperature; however, vertical SCP showed the capacity for

S₂S formation and non-dendritic solidification of this type of alloy with high Si content close to eutectic composition.

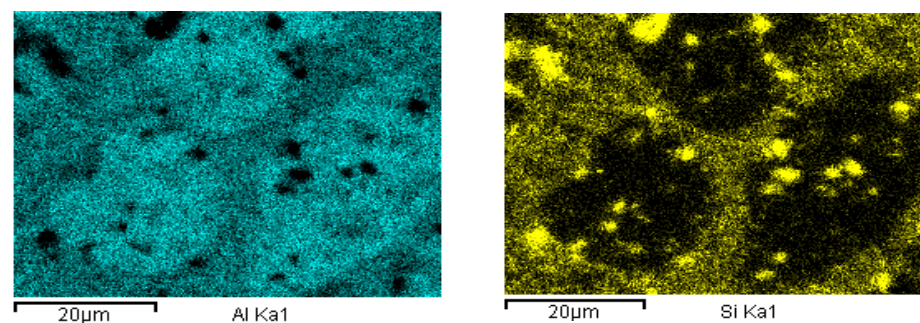


Figure 8. EDS mapping of the non-dendritic $\alpha(\text{Al})$ phase and the eutectic structure in A380 alloy.

4.2. A356 Alloy Processed by Horizontal SCP

The microstructural analysis of the A356 alloy showed the presence of $\alpha(\text{Al})$ phase in a globular shape surrounded by a eutectic structure, as shown in Figure 9. The effect of the pouring temperature on the morphology transition was analyzed. The liquidus temperature for this alloy is 614 °C at 7wt% Si. The solid fraction ($f_{\alpha(\text{Al})}$) is affected by the pouring temperature: $f_{\alpha(\text{Al})} = 0$ when the melt was gravity-poured into the serpentine channel, $0 \leq f_{\alpha(\text{Al})} \leq 0.46$ during slurry formation and the defined limit $f_{\alpha(\text{Al})} \approx 0.46$ at 577 °C. The solid fraction was calculated at the end of the channel according to the measured temperature at that position.

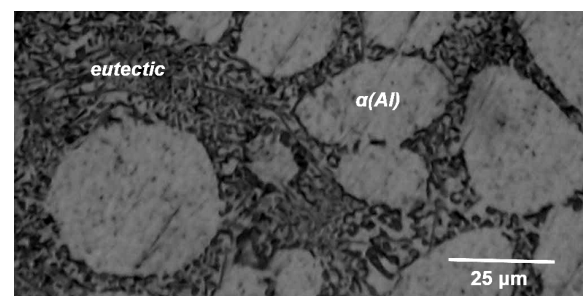


Figure 9. Non-dendritic A356 alloy produced by horizontal SCP.

The solid fraction was calculated by means of the Scheil model according to Equations (1) and (2) for A380 and A356 alloys; the calculations are only valid for hypoeutectic compositions and for the temperature interval between the liquidus and the eutectic transformation. The drawing line for the calculated solid fraction of the A356 alloy showed in Figure 10 is very close to that reported by Mei-Lau Hu et al. by means of the Pandat database [34]. Moreover, Figure 10 contains the traced k coefficient; this calculation is based on the solute distribution, and the solute distribution on both phases does not remain constant and depends on T .

The micrographs in Figure 11 show the microstructural evolution according to the operation parameters. The melt poured and unloaded at 690 °C and 620 °C, respectively, is above the liquidus temperature and the solid appearance; in this case, a small number of globules by chilling and a high retention of dendrites were produced. The measured cooling rate is 5.83 °C/s.

At 660 °C for pouring and 602 °C for unloading, irregular globules at low concentrations of agglomeration were produced due to the insufficient number of nuclei. The cooling rate was 4.83 °C/s, and the solid fraction calculated by Scheil equation at the horizontal SCP unload was $f_{\alpha(\text{Al})} \approx 0.17$.

At 630 °C and 592 °C for pouring and unloading, respectively, smaller globules at an increasing concentration were produced due to the increase of the solid fraction calculated

by the Scheil equation at the channel unload $f_{\alpha(Al)} \approx 0.31$; however, the agglomeration effect persists, probably due to insufficient shear rate during the slurry formation. The cooling rate decreased to 3.16 °C/s compared to the previous tests.

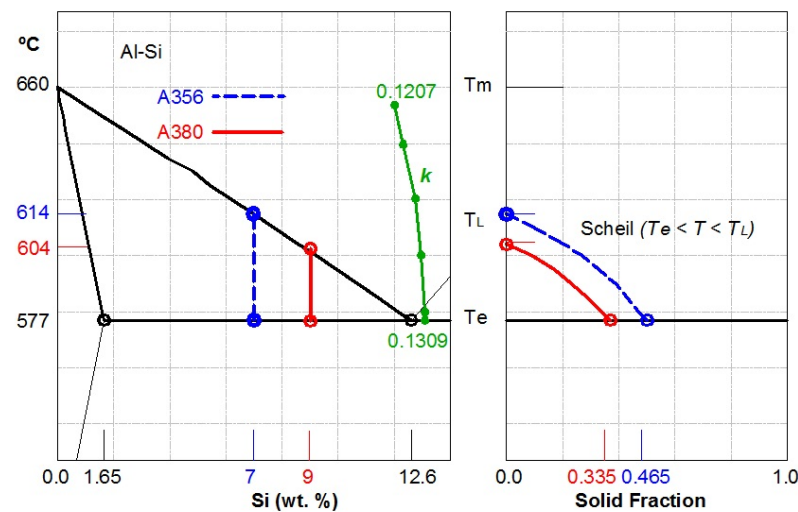


Figure 10. Solid fraction calculated by the Scheil equation for the A380 and A356 alloys.

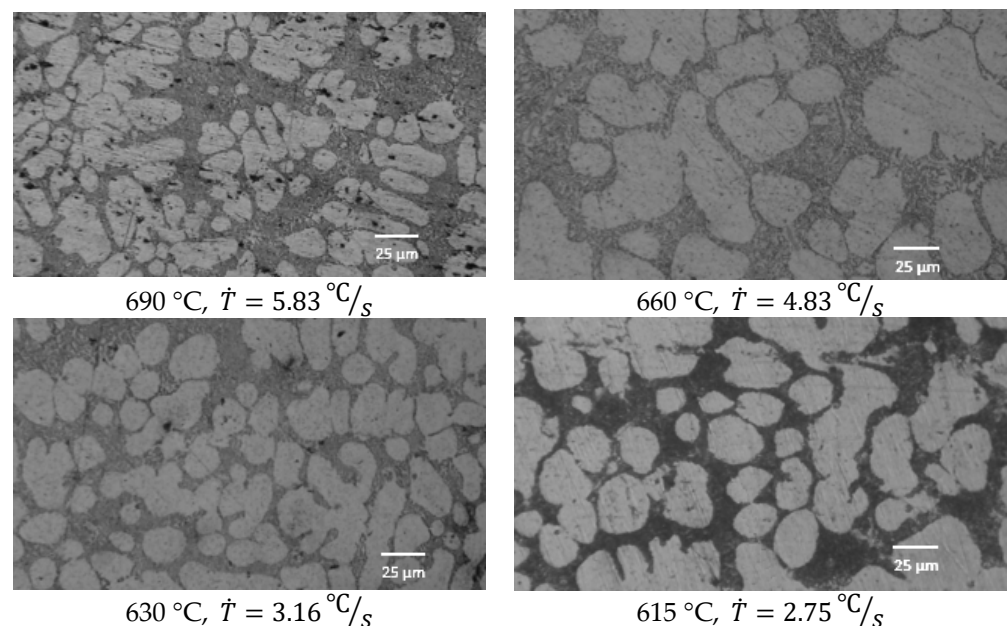


Figure 11. Effect of the pouring temperature and the cooling rate on the solid fraction and shape morphology on A356 alloy produced by horizontal SCP.

Finally, more regular globules were produced at 615 °C for pouring, 582 °C for unloading, the lowest cooling rate $\dot{T} = 2.75 \frac{^{\circ}\text{C}}{\text{s}}$, and solid fraction $f_{\alpha(Al)} \approx 0.41$ (Scheil). The melt was poured close to the solid appearance, the slurry is formed into the horizontal SCP with flow capacity further to the unload position.

Table 3 shows the shape factor (circularity, C) of the globules and their average size. The lowest form factor was obtained at the highest pouring temperature, and this value is consistent with the elongated morphology of the $\alpha(Al)$ phase globules; on the other hand, the highest form factor was obtained from the alloy poured at the lowest temperature (615 °C), where the $\alpha(Al)$ phase globules presented greater circularity.

Table 3. Microstructural parameters of alloy A356 at different pouring temperatures.

Pouring Temperature, (°C)	Globule Size G_{LS} , (μm)	Shape Factor, C
690	48 ± 4	0.41 ± 0.03
660	51 ± 2	0.52 ± 0.03
630	43 ± 2	0.59 ± 0.03
615	39 ± 2	0.68 ± 0.03

5. Conclusions

Equiaxed grains in the $\alpha(\text{Al})$ phase uniform in size and distribution are produced by vertical SCP due to the chilling effect associate to the increase on curve number and decrease on curve diameter; however, the alloy was totally solidified into the channel at the end of the route. The non-dendritic A380 alloy produced by vertical SCP is a notable mention even though the technical difficulties such as the low semi-solid temperature interval, the top on availability of solid fraction and the gravity-pouring.

The horizontal SCP concept is introduced as a new design with some advantages over vertical SCP, notably the improvement on flow development and heat transfer; the results suggest that the chilling effect and the shearing by self-stirring produce the capacity for the change of morphology of the primary solid; moreover, a short route including a smaller number of turns increases the yield with the minimal consumption of the alloy in the channel.

The effect of pouring temperature on the solid fraction produced in the slurry and the shape conversion of the $\alpha(\text{Al})$ phase on A356 alloy was studied. The top of the solid fraction was produced by pouring close to the liquidus temperature, and in this condition, enough solid alloy was available to modify its morphology. The increase in pouring temperature decreased the solid fraction, causing insufficient nuclei, irregular globules, and agglomeration. At a high pouring temperature, the limited availability of the solid phase produced a low number of globules, and the dendritic growth was dominant.

The two SCP methods described in this study for S2S formation have shown the ability to modify the primary solid from dendrites to equiaxed grains on the processed alloys. The morphological transition of the $\alpha(\text{Al})$ phase is irreversible; the probable mechanisms for the shape evolution of the primary solid are exposed and proposed in the schematic diagram in Figure 3. The experiments were carried out to obtain on one hand, a chill of the constructed runner in addition to grain refinement as adequate nucleation agents; on the other hand, self-stirring at high shear rate to produce the slurry with thixotropic behavior by the morphology evolution of the $\alpha(\text{Al})$ phase.

The vertical and horizontal SCP tests were assisted by gravity-pouring with its own flow characteristics such as pressure, velocity, kinetic energy, etc. A suitable design of the serpentine channel contained within a chilling device installed inside a mold for die-casting could be a study of interest to modify those flow conditions. Two ideas for further experiments are suggested with respect to the location of the SCP block: on one hand, it could be placed inside the mold between the injection plunger and the gate to the castings; and on the other hand, it could be located in the charge gate of the cold chamber of the die-casting machine. In both cases, the melt should be poured into the inlet of the SCP channel close to the liquidus temperature of the alloy.

Author Contributions: Conceptualization, formal analysis, writing-original draft preparation, H.A. (Hernández Alfredo); supervision, resources, funding acquisition, project administration, writing-review and editing, C.J.F.; investigation, methodology, H.A. (Hernández Aldo); validation, writing-review and editing, S.M.Á. All authors have read and agreed to the published version of the manuscript.

Funding: The authors acknowledge financial support from National Council for Humanity, Science and Technology (CONAHCyT), SIP-IPN and ESIQIE.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Spencer, D.B.; Mehrabian, R.; Flemings, M.C. Rheological behavior of Sn-15 pct Pb in the crystallization range. *Metall. Mater. Trans. B* **1972**, *3*, 1925–1932. [\[CrossRef\]](#)
2. Wannasin, J. *Semi-Solid Slurry Forming of Alloys*; North American Die Casting Association NADCA: Arlington Heights, IL, USA, 2013.
3. Kirkwood, D.; Suéry, M.; Kapranos, P.; Atkinson, H.; Young, K. *Semi-solid Processing of Alloys*; Springer: Berlin/Heidelberg, Germany, 2010. [\[CrossRef\]](#)
4. Li, G.; Lu, H.; Hu, X.; Lin, F.; Li, X.; Zhu, Q. Current Progress in Rheoforming of Wrought Aluminum Alloys: A Review. *Metals* **2020**, *10*, 238. [\[CrossRef\]](#)
5. Modigell, M.; Pola, A.; Tocci, M. Rheological Characterization of Semi-Solid Metals: A Review. *Metals* **2018**, *8*, 245. [\[CrossRef\]](#)
6. Pola, A.; Tocci, M.; Kapranos, P. Microstructure and properties of semi-solid alloys: A literature review. *Metals* **2018**, *8*, 181. [\[CrossRef\]](#)
7. Menargues, S.; Baile, M.T.; Martin, E.; Raya, O.M.; Picas, J. New mechanical stirring system to study the rheological behavior of A380 second melting aluminium alloy. *Res. Sq.* **2023**. [\[CrossRef\]](#)
8. Rosso, M. Thixocasting and rheocasting technologies, improvements going on. *J. Achiev. Mater. Manuf. Eng.* **2012**, *54*, 110–119.
9. Martinez, R.A.; Flemings, M.C. Evolution on particle morphology in semisolid processing. *Metall. Mater. Trans. A* **2005**, *36*, 2205–2210. [\[CrossRef\]](#)
10. Abdulrahman, K.; Gonda, V.; Réger, M.; Varga, P. Comparison of Microstructure, Density and Shrinkage Porosity for Casting and Rheocasting of AlSi7Mg Alloy. *Res. Sq.* **2023**.
11. Hu, X.G.; Zhu, Q.; Midson, S.P.; Atkinson, H.V.; Doug, H.B.; Zhang, F. Blistering in semi-solid die casting of aluminium alloys and its avoidance. *Acta Mater.* **2017**, *124*, 446–455. [\[CrossRef\]](#)
12. Salleh, M.S.; Omar, M.Z.; Syarif, J.; Mohammed, M.N. An Overview of Semisolid Processing of Aluminium Alloys. *Int. Sch. Res. Not.* **2013**, *2013*, 679820. [\[CrossRef\]](#)
13. Kotadia, H.R.; Hari, B.N.; Zhang, H.; Arumuganathar, S.; Fan, Z. Solidification Behavior of Intensively Sheared Hypoeutectic Al-Si Alloy Liquid. *Metall. Mater. Trans. A* **2010**, *42*, 1117–1126. [\[CrossRef\]](#)
14. Nafisi, S.; Ghomashchi, R. *Semi-Solid Processing of Aluminum Alloys*; Springer International Publishing: Cham, Switzerland, 2016. [\[CrossRef\]](#)
15. Boluri Gashti, A.H.; Abedi, H.R.; Salehi, M.T. Microstructure evolution and constitutive modeling of as-cast A356 aluminum alloy in semi-solid regime. *J. Mater. Res. Technol.* **2023**, *24*, 7720–7731. [\[CrossRef\]](#)
16. Brabazon, D.; Browne, D.J.; Carr, A.J. Experimental investigation of the transient and steady state rheological behavior of Al-Si alloys in the mushy state. *Mater. Sci. Eng.* **2003**, *A326*, 69–80. [\[CrossRef\]](#)
17. Honarmand, M.; Salehi, M.; Shabestari, S.G.; Saghaian, H. Impact strength and structural refinement of A380 aluminum alloy produced through gas-induced semi-solid process and Sr addition. *Trans. Nonferrous Met. Soc. China* **2022**, *32*, 1405–1415. [\[CrossRef\]](#)
18. Wannasin, J.; Flemings, M. Development of the Gas Induced Semi-Solid Metal Process for Aluminum Diecasting Applications. In Proceedings of the 10th International Conference on Semi-Solid Processing of Alloys and Composites, Aachen, Germany, 16–18 September 2008; pp. 97–102.
19. Wannasin, J.; Janudom, S.; Rattanochaikul, T.; Canyook, R.; Burapa, R.; Chuchee, T.; Thanabumrungskul, S. Research and development on the gas induced semi solid process for industrial applications. In Proceedings of the 11th International Conference on Semi-Solid Processing of Alloys and Composites, Busan, Republic of Korea, 11–13 September 2010; pp. 544–548.
20. Liu, Y.; Gao, M.; Meng, S.; Fu, Y.; Li, W.; Li, C.; Guan, R. Solidification behavior and enhanced properties of semi-solid Al-8.5Si-0.5Fe alloys fabricated by rheo-diecasting. *J. Mater. Res. Technol.* **2022**, *19*, 3160–3171. [\[CrossRef\]](#)
21. Li, N.-Y.; Mao, W.-M.; Geng, X.-X. Preparation of semi-solid 6061 aluminum alloy slurry by serpentine channel pouring. *Trans. Nonferrous Met. Soc. China* **2022**, *32*, 739–749. [\[CrossRef\]](#)
22. Liu, Z.-Y.; Mao, W.-M.; Wang, W.-P.; Zheng, Z.-K. Preparation of semi-solid A380 aluminum alloy slurry by serpentine channel. *Trans. Nonferrous Met. Soc. China* **2015**, *25*, 1419–1426. [\[CrossRef\]](#)
23. Liu, Z.-Y.; Mao, W.-M.; Wang, W.-P.; Zheng, Z.-K.; Yue, R. Investigation of rheo-diecasting mold filling of semi-solid A380 aluminum alloy slurry. *Int. J. Miner. Metall. Mater.* **2017**, *24*, 691–700. [\[CrossRef\]](#)
24. Das, P.; Kumar, M.; Samanta, S.; Dutta, P.; Ghosh, D. Semisolid Processing of A380 Al Alloy Using Cooling Slope. *Mater. Manuf. Process.* **2014**, *29*, 422–428. [\[CrossRef\]](#)
25. Das, P.; Samanta, S.K.; Das, R.; Dutta, P. Optimization of degree of sphericity of primary phase during cooling slope casting of A356 Al alloy: Taguchi method and regression analysis. *Measurement* **2014**, *55*, 605–615. [\[CrossRef\]](#)
26. Das, P.; Samanta, S.K.; Kumar, P.; Dutta, P. Phase Field Simulation of Equiaxed Microstructure Formation during Semi-solid Processing of A380 Alloy. *ISIJ Int.* **2014**, *54*, 1601–1610. [\[CrossRef\]](#)

27. Hirt, G.; Kopp, R. (Eds.) *Thixoforming, Semi-Solid Metal Processing*; Wiley-VCH: Weinheim, Germany, 2009; pp. 344–345.
28. Khalifa, W.; El-Hadad, S. Ultrasonication effects on the microstructure characteristics of the A380 die cast alloy. *Int. J. Met.* **2019**, *13*, 865–879. [[CrossRef](#)]
29. Kurz, A.W.; Fisher, D.J. *Fundamentals of Solidification*; Trans Tech Publications Ltd.: Wollerau, Switzerland, 1992; ISBN 0-87849-804-4.
30. Bonatti, R.S.; Bortolozzo, A.D.; Baldo, R.F.G.; Poloni, E.; Osório, W.R. Anisotropic Tensile and Compressive Strengths of Al–4 wt.%Cu Alloy Powder: Part 1—Effects of Compaction Loads and Heat Treatments. *Metals* **2023**, *13*, 1710. [[CrossRef](#)]
31. Dantzig, J.A.; Rappaz, M. *Solidification*; CRC Press: Cham, Switzerland, 2009.
32. Hernández, A.; Chávez, F.; Hernández, R. Simplified rheocasting of Al-Si alloys sheared by mechanical stirring. *Key Eng. Mater.* **2015**, 651–653, 1545–1550.
33. Hernández, A.; Chávez, J.F. Stir Casting and Atmospheric Pouring of A380 Alloy with Sr Addition. *AIP Conf. Proc.* **2019**, *2113*, 140003. [[CrossRef](#)]
34. Hu, M.-L.; Guo, H.-M.; Ma, T.-F.; Jin, H.-L. Microstructure evolution in semi-solid A356 aluminium alloy treated by ICTE process. *Mater. Sci. Technol.* **2023**, *39*, 1050–1058. [[CrossRef](#)]
35. Dantas, A.V.R.; Brollo, G.L.; Tamayo, D.V.; Zoqui, E.J. Thixoforming of an Al-Si-Zn-Mg Alloy—Thermodynamic Characterization, Microstructural Evolution and Rheological Behavior. *Mater. Res.* **2021**, *24*, e20200313. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.