Parameters Influencing Dendritic Structure to Improve the Properties of As-Cast Aluminium Alloys

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Dendritic microstructures are formed in most alloys during processes such as casting and welding. A semi-empirical model named ALPROP has been developed for the calculation of tensile properties and hardness in AlSiMg (Fe) foundry alloys. With chemical composition, dendrite arm spacing (DAS) and heat treatment parameters as input, the model calculates tensile properties and hardness for material in as-cast, solid-solution, heat-treated and in artificially-aged condition. It is seen that with decrease in dendritic arm spacing, the tensile strength, hardness and fatigue life increases. However, there is not much effect found on the yield strength. The present study makes an estimation of an automotive engine piston mechanical properties and fatigue life based on some characteristics of metallurgical microstructure. Alloy systems such as, Al-Si and Al-Si-Mg are taken to discuss the dentritic structure. Secondary dendritic arm spacing (SDAS) and grain size have great bearing on mechanical properties. Hence along with SDAS, more emphasis should also be given on the grain refinement to get better mechanical properties in the as-cast structure. The present study describes the effects of grain refinement in Al-10.2%Si using a newly developed process called as MCAST (melt conditioning by advanced shear technology). As a result, understanding the mechanisms for morphological selection of dendritic structures will be a key in the development of next-generation light-weight alloys used in automotive and aerospace applications.

Introduction

Dendritic solidification frequently occurs under conditions which are far from equilibrium. Given these circumstances, regions of solute-rich liquid can be trapped between the dendrite arms and solidify eventually to solute-rich solid regions. This in turn leads to the development of a "banded" microstructure when the material is subsequently processed by rolling or other mechanical fabrication methods (Fig. 1).

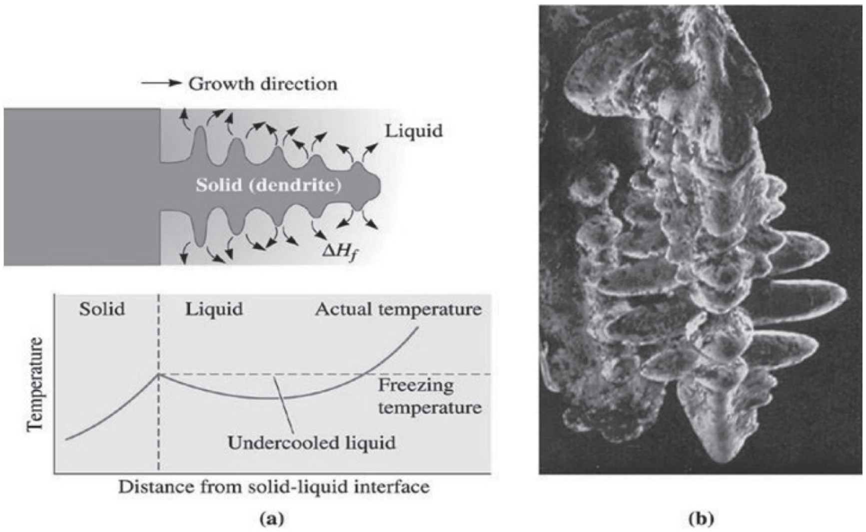

Fig.1: (a) If the liquid is under-cooled, a protuberance on the solid-liquid interface may grow rapidly as a dendrite. (b) Scanning electron micrograph of dendrites in steel.

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Formation of Mushy Zone

Dendrites exist between a fully solid zone adjacent to the mould surface and a fully liquid zone at the centre. This liquid-solid zone is called the mushy zone. The mushy zone consists of dendrites surrounded by liquid metal. In many cases, the mushy zone will occupy the entire casting section for a period of time. Alloys solidifying with a mushy zone normally do not have columnar grain growth. The dendritic structures that form in the mushy zones are often highly ramified and tend to be reasonably uniform in overall appearance, resulting from the growth of multiple primary dendrites and the subsequent development of secondary, tertiary, and higher order-side branches[6] (Fig.2).

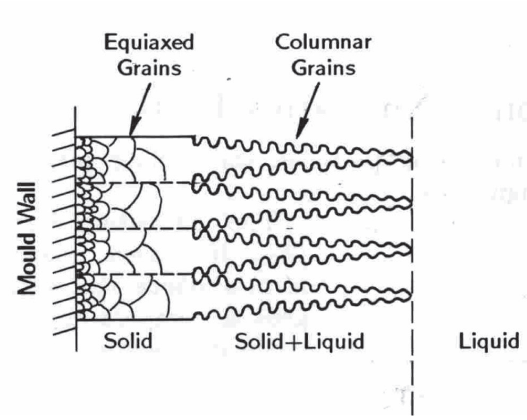

Fig. 2: Formation of a mushy zone.

The width of a mushy zone increases with the temperature range over which the alloy solidifies. A pure metal will have a very narrow mushy zone. In carbon steels, the width of mushy zone increases with the increase of percentage of carbon. Alloys (like cast steels) which have relatively steep temperature gradients (because of their low thermal conductivities and high freezing temperatures) tend to possess narrow mushy zones. Since chilling can make temperature gradient still steeper, it further narrows down the mushy zone.

Depending on freezing range and temperature gradient –

$\alpha = \Delta T_f / G$

Where,

α – Width of mushy zone

ΔT_f – freezing range, k

G - Temperature gradient, dt/dx, K/m

Micro-Segregation in Dendritic Structure

Micro-segregation has industrial importance as it influences the mechanical properties, such as yield strength of the alloys[7]. Also dendrite arm spacing is very important in heat treatment. Figure 3 shows the relationship between residual micro-segregation (δ) and a dimension-less parameter Dt/l^2 where D is the diffusion coefficient in the solid at the temperature of homogenisation, t is the homogenisation time, and l is a characteristic diffusion distance of the order of dendrite arm spacing.

Where,

$\delta = (C_M - C_m) / (C^0_M - C^0_m)$

C_M: maximum solute concentration of element l (in inter-dendritic spaces) at t

C_m : minimum solute concentration of element l (in inter-dendritic spaces) at t

C^0_M: initial value of C_M

C^0_m : initial value of C_m

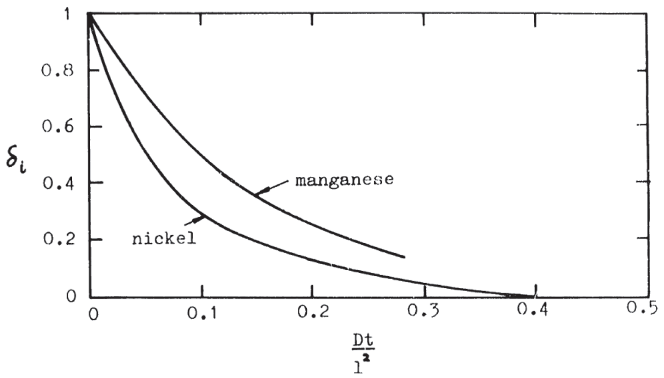

Fig.3: Residual segregation index δ vs. dimensionless homogenisation parameter for low alloy steel (T. Z. Kattamis and M. C. Flemings, Transaction of the Metallurgical Society of AIME, 233,998,1965).

ALPROP Model

ALPROP[8] has been developed for the calculation of tensile properties and hardness in AlSiMg (Fe) cast alloys with chemical composition, dendrite arm spacing (DAS) and heat treatment parameters as input for material in as-cast.

ALPROP model has proved to be a useful tool for tailoring mechanical properties by correct choice of chemical composition and process parameters, for analysing consequences and identifying possible actions when having unintended process variations, identifying improvement potentials and for training of foundry staff.

Hypoeutectic AlSiMg primary cast alloys combines excellent castability with the possibility of obtaining castings with high ductility, fracture toughness and fatigue properties. In addition, moderate to high strength can be achieved by applying heat treatment to the castings. These properties make the alloys suited for demanding applications within the automotive segment. Products as wheel rims, master brake cylinders and structural parts (ex. sub-frames) are made from AlSiMg primary cast alloys.

The ultimate tensile stress UTS can be calculated if the strain hardening of the tensile sample is known. ALPROP applies a Ludvig stress-strain law for this purpose:

$UTS = YS + K\varepsilon_u^{\,n}$

Where

$K = (250 + 100{*}Mg)\, e^{3.5/DAS}$

$\varepsilon_u = \ln(1 + A_u/100)$

$n = 0.5$

The equation expresses that the strain hardening increases with increasing Mg and decreasing DAS. The value 0.5 is prescribed as a typical value for n in aluminium alloys.

Vickers hardness HV is expressed by the same stress-strain law, making the assumption that a hardness indentation in average causes a true strain of 0.08. The proportionality factor of this strain, between the stress and the hardness is 3.

$HV = 1/3(YS + K{*}0.08^n)$

Mechanical Properties and Fatigue Life Assessment of Cast Automotive Engine Piston

Assessment of components failure is strongly dependent on failure localisation. The component point where failure occurs strongly depends on local properties. And these local properties are also influenced by the processing technique[9]. In the specific case of an engine piston, local properties are influenced by the casting technique. Mechanical properties (tensile strength, tensile strain, Young's modulus, etc.) as well as fatigue properties (fatigue life) are very dependent on casting method. One of the important variables affected by the casting technique is the cooling rate and the cooling rate strongly restricts the microstructure.

The automotive engine pistons are usually cast in near-eutectic aluminium-silicon alloys. The structure and properties of cast aluminium-silicon eutectic alloys are dependent on the cooling rate, composition, modification, heat treatment operations, etc.[10,11,12]. It is also necessary to know all the factors which are influencing the characteristics of the final casting part: type of casting, temperatures (melt and mould), cooling rate, refiners etc.[13,14,15], and to know it in the different parts of the component because they strongly change along the same component.

A number of papers have been published showing several relations that estimate the tensile strength with other different microstructure characteristics. Bernsztejn proposed a relation to calculate the average strength as a linear function of the volume fraction of silicon[16]:

$$\sigma_\alpha.V_V^\alpha + \sigma_{Si}.V_V^{Si} \qquad (1)$$

where, σ_α and σ_{Si} are rupture strengths in the volume unit. This formula neglects the influence of the morphology, the average size, and the distribution of brittle particles.

Mandal[17] presented a correlation between tensile strength (σ) and silicon particle size for aluminium-silicon alloy containing 17-27% Si without considering the secondary dendritic arm spacing.

Another relationship between tensile strength and secondary dendrite arm spacing and the size of silicon lamellas in interdendritic eutectic regions, was proposed by (ASM Int. 2004):

$$\sigma = K + K_2\,\gamma^{-0.5} + K3\,\lambda^{-0.5} \quad (2)$$

Where σ is the tensile strength, k, k_2 and k_3 are empirical constants, γ is the size of silicon lamellas in interdendritic eutectic regions and λ is the secondary dendrite arm spacing.

Secondary dendrite arm spacing (SDAS) is also in attention of researcher and generates several models to estimate tensile strength[18]:

$$UTS = -1.4399\ .SDAS + 340\ [MPa] \qquad (3)$$

where, UTS is ultimate tensile strength and SDAS is secondary dendrite arm spacing.

Determining Dendritic Arm Spacing

The material used to cast the piston was a near-eutectic aluminium-silicon alloy. The SDAS was quantified by identifying and measuring small groups of well-defined secondary dendrite arms on the screen of the image analyser. The value of SDAS was then determined using SDAS=d/nM, where d is the length of the line drawn from edge-to-edge of measured arms, M is the magnification, and n is the number of dendrite arms (Fig. 4).

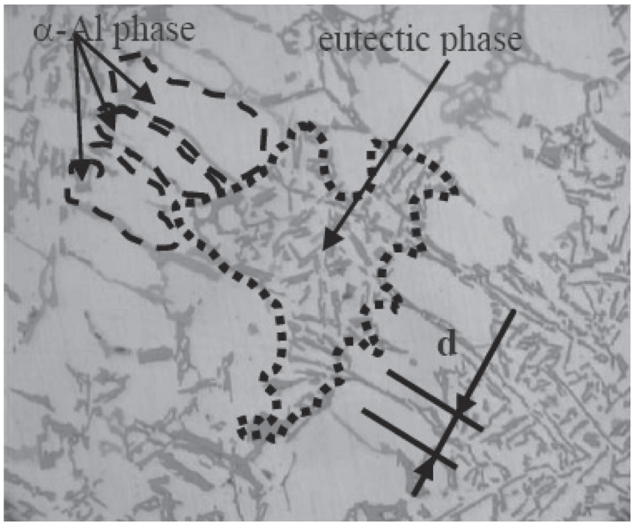

Fig.4: Microstructure Analysis.

Example:

A commercial engine piston obtained by gravity casting on permanent mould was studied (Fig. 5).

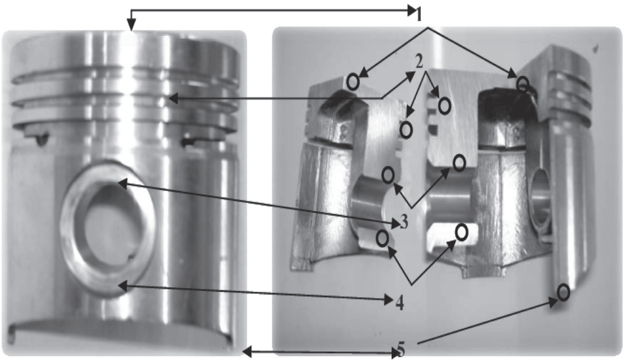

Fig. 5: Regions of piston studied: 1-top position, 2- piston ring position, 3- top pin position, 4- down pin position, 5- skirt position

The secondary dendrite arm spacing measured values are presented. The SDAS shows an increase of about 90% from skirt position -24 μm to top position -47 μm (Fig. 6).

From volume fraction quantification of constituent phases (Fig. 7) is noticed that the volume fraction of eutectic phase is increasing from position 1 (top position) to position 5 (skirt position) which is in opposite relation with the α-Al dendrite phase.

Analysing together volume fraction of the eutectic phase with the SDAS results it is interesting to highlight the fact that there exists a relation between them: the region with higher values of the SDAS has small amount of eutectic phase.

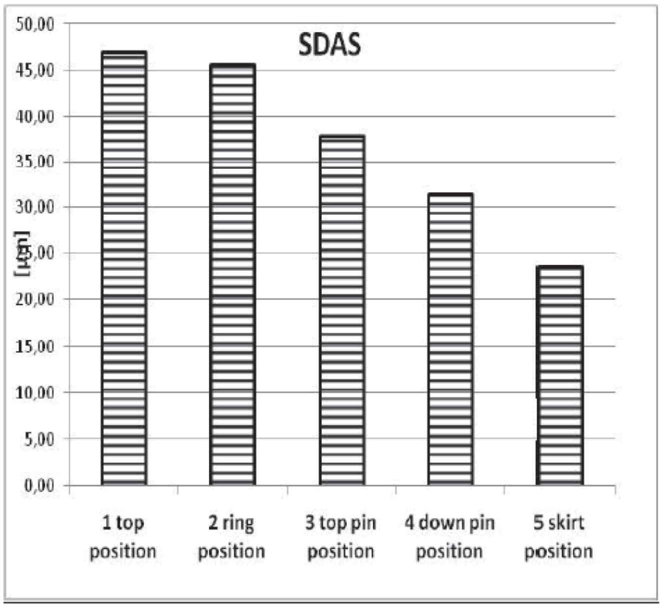

Fig. 6: Secondary dendrite arm spacing.

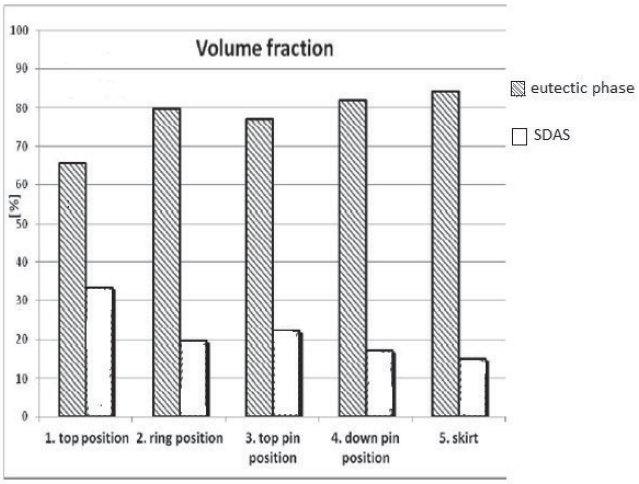

Fig. 7: Volume fraction of eutectic and α-aluminium dendrite phase.

Table-1 : UTS Calculated Using Eq. 3

Position	SDAS [μm]	UTS [Mpa]
1. Top Position	46.98	202.36
2. Ring Position	45.60	204.35
3. Top Pin Position	37.94	215.38
4. Down Pin Position	31.47	224.69
5. Skirt Position	23.64	235.97

Mechanical and mechanical fatigue failures occur in critical localisations. Critical localisations are not those where stresses are higher than in the rest of component but where the ratio of local stress vs. ultimate tensile local strength is higher. Thus, prediction of the cast aluminium component properties should be made based on local material mechanical properties which makes possible calculate the ratio of stress vs. UTS. Local mechanical and fatigue properties may be obtained by local metallurgical features.

The decreasing tendency of SDAS could be explained by the differences of cooling rates in different places of the mould. As is already known from literature, the secondary dendrite arm spacing, for a given alloy, is influenced mainly by the cooling rates.

Effect of Grain Refinement

Microstructural refining of metallic alloys has been one of the most important subjects in the field of metallurgy. The reason lies in the fact that many of the mechanical properties of the alloys largely depend on the size, shape and distribution of grains in the microstructure[19]. The dependence of grain size on mechanical properties can be given by the Hall-Petch relation

$$\sigma_0 = \sigma_i + kd^{-1/2}$$

Where,

σ_o is yield strength

σ_i is frictional stress opposing motion of dislocation

k is the measure of extent to which dislocations are pile-up at the barriers

d is average grain diameter

Grain size has a very important effect on the morphology of dendrites. Larger grains consist of elongated dendrites whereas as the grain size decreases, the dendrites also reduce in size, dendritic arms becomes equiaxed and results in nodular colony of dendrites which are much finer. Hence, reduction in the grain size results in better mechanical properties of as-cast structure. Generally in most alloys, if the cooling rate increases the primary dendrite size of the alloys decreases. The secondary dendrite arm spacing of the alloys was also decreased with the increasing cooling rate. Hence, cooling rate also has an effect on the grain size. Al-Si alloys have wide industrial usage in the areas of automotive, aerospace and military applications due to their excellent castability, high specific strength, excellent corrosion resistance and good wear properties[20]. Therefore, it is very important to control microstructural evolution, casting defects and mechanical property in the finished Al-Si casting alloys.

It has been recognised that the aluminium alloys' dendritic structure can be modified to an equiaxed grain by two main approaches, namely :

(i) Chemical modification, which produced a fine grain structure through the addition of several elements, such as Al-Ti-B and Al-Ti-C etc. and

(ii) Physical grain refinement through the external force applied to induce fluid flow during solidification in order to refine grain size, such as low-frequency mechanical mould vibration, mechanical or electromagnetic stirring or ultrasonic irradiation of melt.

Recently, researchers at BCAST, (Brunel Center for Advanced Solidification Technology) Brunel University, have developed a MCAST (melt conditioning by advanced shear technology) process[26] to study the solidification behaviour of aluminium and magnesium alloys under intensive shearing[21-24]. The MCAST unit can offer high shear rate and high intensity turbulence, which promotes primary phase to grow into globular morphology. The main objective of this study was to design a practical alternative of the chemical grain refinement by using intensive shearing to refine Al-10.2%Si cast ingot[25].

Figure 8(a) and (c) presents the microstructures for the alloy specimen solidified at 590 °C and 650 °C, respectively. It is evident from Fig. 8(c) that the solidified morphology consists of large dendrite grains (about millimeters long) for samples cast at higher superheat. In contrast to conventional casting, remarkable grain refinement was observed when the melt was sheared in the MCAST unit. Al-10.2% Si sheared cast microstructure at 590°C and 650 °C presented in Fig.8(b) and (d), respectively. The grain structure throughout the specimen is equiaxed and considerably finer than the conventional cast sample. In contrast to conventional casting, remarkable grain refinement was observed when the melt was sheared in the MCAST unit.

Al-10.2% Si sheared cast microstructure at 590°C and 650°C are presented in Fig. 8(b) and (d), respectively. The grain structure throughout the specimen is equiaxed and considerably finer than the conventional cast sample.

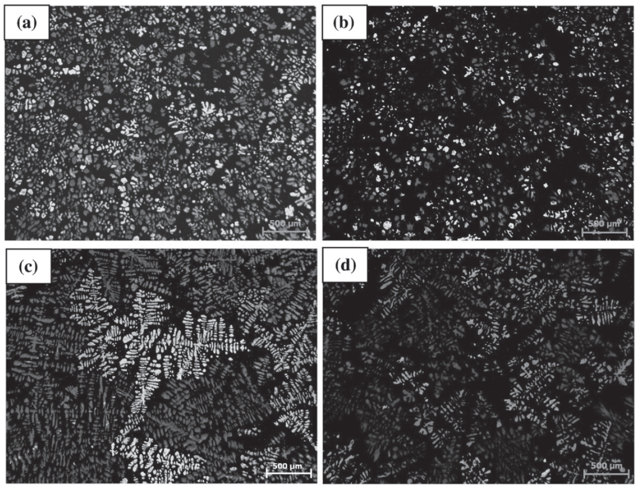

Fig. 8: Optical micrographs of specimen (a), (c) conventional and (b), (d) sheared, pouring temperature (a), (b) 590°C and (c),(d) 650 °C.

Figure 9 shows the grain size as a function of casting temperatures. Microstructural refinement is achieved by intensive shearing without any involvement of a deliberate chemical addition.

Figure 9 clearly reveals that the grain size achieved after liquid shearing is much finer compared with the conventional casting process, even at higher superheat casting. In comparison, the extent of the grain refinement achieved due to melt shearing in conjunction with the liquid casting is more remarkable than refinement achieved by the low superheat casting alone.

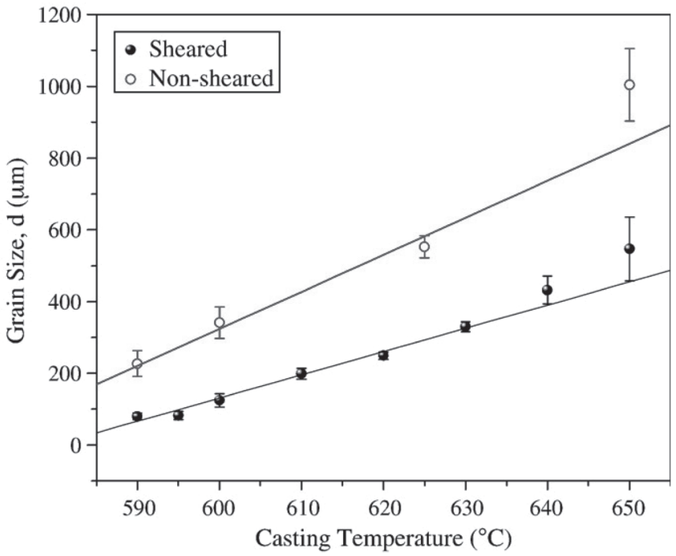

Fig. 9 : Variation of the grain size as a function of casting temperature for Al-10.2%Si alloy cast (with sheared and non-sheared).

In addition to fine grain structure, MCAST process offers additional benefits such as refinement of intermetallic phases and their uniform distribution when compared to other dynamic solidification conditions. Intensive shearing disperses harmful oxide inclusion clusters uniformly and breaks oxide films into fine inclusions. This process is also applicable for mass production both in semi-solid and liquid state without any processing difficulties with increased tolerance to the impure elements (e.g., iron), so more scrap metal can be directly recycled in-house without going through chemical purification.

Conclusion

This paper reviews the various parameters which affect the dendritic structure and relationship between the dendritic arm spacing and mechanical properties like tensile strength, fatigue strength and hardness in aluminium alloys. Thus, it gives us idea of controlling the properties of final as-cast product. Secondary dendrite arm spacing of alloys decreases with increasing cooling rate during solidification. As the secondary dendrite arm spacing decreases, the hardness, tensile strength, percentage elongation and impact energy of these alloys increase. The improved mechanical characteristics of cast structures having smaller dendrite spacing are due largely to the shorter wavelength of the periodicity of the microsegregation. ALPROP[11] has been developed for the calculation of tensile properties and hardness in Al-Si-Mg, (Fe) foundry alloys with chemical composition, dendrite arm spacing (DAS) and heat treatment parameters as input for material in as-cast. Finer grain structure was obtained using MCAST process in a Al-10.2%Si alloy. It also offers additional benefits such as refinement of intermetallic phases and their uniform distribution.

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