Modeling Primary Dendrite Arm Spacings in Resistance Spot Welds
Part I — Modeling Studies

Relationships between solidification conditions and primary dendrite spacings are reviewed and incorporated into a thermal model for resistance welding

BY J. E. GOULD

ABSTRACT. Hold time sensitivity is a potential concern when cold-rolled high-strength low-alloy sheet steels are used in resistance spot-welded applications. Hold time sensitivity is defined by cracking that occurs along the faying surface of the weld on peel testing when conventional hold times are used, and does not occur when reduced hold times are used. Hold time sensitivity is related to solidification cracking in the steel; however, it is believed that steel hardenability may also play a role. As an aid to understanding of solidification cracking in resistance spot welds, it is necessary to have an understanding of how the solidification structure develops. In this work, solidification structures in resistance spot welds have been characterized by the primary dendrite spacing. Primary dendrite spacings have been modeled by using a combination of numerical thermal modeling and closed-form primary dendrite spacings modeling. Numerical thermal modeling was used to predict solidification conditions in these welds. These solidification conditions were then used in the primary dendrite spacings model to predict the local spacings.

This work was conducted in two parts. Part I is covered in this paper, and details the modeling work done to characterize solidification conditions, and the relationships between solidification conditions and primary dendrite spacings. Part II covers experimental work done to measure primary dendrite arm spacings in spot welds made on a range of sheet thicknesses and steel compositions. This is presented in a subsequent paper.

The thermal modeling results presented here showed the solidification conditions (thermal gradient and the solidification rate) vary by almost an order of magnitude from beginning to end of nugget solidification. The slowest solidification rates and shallowest thermal gradients were noted at the last regions to solidify. Solidification conditions were also found to vary as a function of steel gauge, with heavier gauges resulting in reduced thermal gradients and solidification rates. Estimations of relative variations in primary dendrite spacings were also made. It was found that increasing sheet thickness resulted in increased dendrite spacings. Also, spacings increased for a given spot weld nugget as solidification progressed from the edge of the nugget to the weld centerline.

Introduction

During the past 10 to 15 years, the modeling of structures in weldments has included studies in modeling grain growth (Refs. 1-3), second-phase particle dissolution (Ref. 1), austenite decomposition (Refs. 4-7) and solidification (Ref. 8). The underlying assumption in most of these works has been that models describing various transformations in metals (either liquid = > solid or solid = > solid) have been previously explored in the various branches of metallurgy. Structural changes in weldments can then simply be estimated by integrating these models under the appropriate thermal cycle. In this vein, there has been considerable work. However, virtually all has been accomplished with respect to the arc welding process, and, particularly, arc welding various plate steels.

KEY WORDS

Resistance Spot Weld Modeling
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J. E. GOULD is with Edison Welding Institute, Columbus, Ohio.
(Refs. 1–7). This work examines the use of such modeling to address a specific aspect of resistance spot welding, the scale of the solidification structure.

The impetus of this work has been to understand the effect known as hold time sensitivity during resistance spot welding. Hold time in resistance spot welding is that time, after termination of the current, in which the part is held under force in the welding machine to allow the weld to solidify. Hold time sensitivity, as defined in many automotive company specifications, relates to variations in fracture characteristics on peel testing (Refs. 9, 10) as a function of this hold time. A material is considered to be hold time sensitive if two conditions are met. First, after conventional hold times (on the order of one second), cracking is observed along the bond or faying surface. Second, when a short hold time is used, peel testing results in a "button pull" or acceptable fracture. The occurrence of hold time sensitivity indicates that bond line fracture of welds can occur under some sets of resistance spot welding conditions.

Not surprisingly, materials showing hold time sensitivity are generally not considered acceptable for safety-critical applications. The concern is that if hold time sensitive materials are used, conditions would arise where welds with poor failure characteristics would exist in these applications. Although there is considerable evidence that limited hold time sensitivity does not necessarily degrade weld performance (Refs. 11–13), there is concern over manufactured product liability.

Hold time sensitivity has become a point of concern with the application of HSLA steels. Hold time sensitivity was originally thought to be related to material hardenability (Refs. 11, 13). This phenomenon has been strongly correlated with a number of alloy additions used in fabricating HSLA steels (Refs. 11–13). Hold time sensitivity clearly increases with increasing C and P levels. For conventional gauges of steels, some general guidelines have even been established regarding acceptable levels of these additions in preventing hold time sensitivity. Increasing S, although only a tramp element in these steels, has also been found to increase hold time sensitivity.

Detailed examinations of both fracture surfaces and partially cracked welds showing hold time sensitivity have indicated, however, that hold time sensitivity may be more directly related to solidification cracking (Ref. 14). These examinations have clearly shown that when hold time sensitivity cracking occurs, the cracks follow both laying surface and interdendritic porosity. It appears that these lines of residual porosity act as a fast fracture path for failure of the weld on peel testing, resulting in the unacceptable failure mode. It is believed that weld hardenability may play a secondary role on these failures (Ref. 14). That is, while the initial fracture sites and paths may be defined by solidification-related events, the actual susceptibility of the weld-to-crack propagation along these paths is probably defined by the microstructure. This synergistic effect, however, has yet to be examined.

As hold time sensitivity appears to be related to solidification cracking, there should be some similarities in how various additions to the steel affect these two concerns. In steels, the most common alloy additions which both segregate heavily to the liquid and strongly suppress the melting temperature (increasing solidification crack sensitivity) are C, P and S. Not surprisingly, as mentioned above, these additions also have the strongest effect on hold time sensitivity.

Solidification cracking is generally considered to result from a combination of three effects:

1) Extensive suppression of the local liquidus temperature by progressive rejection (or absorption) of solute during solidification.

2) Contractual strains associated with cooling of the solidified material.

3) Lack of additional liquid to accommodate the volume change associated with this cooling shrinkage (Ref. 15).

Spot welding, when done in the recommended manner (Ref. 16), creates an ideal environment for this solidification cracking. Solidification generally initiates at the two opposing sides of the weld nugget at surfaces closest to the welding electrodes, and proceeds in a normal direction terminating at the nugget centerline. The effect is to simultaneously partition solute (k < 1) to the weld centerline, while contracting the growing dendrites due to the steep thermal gradient in the developing solid. The result is the almost unavoidable occurrence of solidification-related shrinkage cavities in resistance welds. The severity of this solidification cracking is a function of both weld geometry and, as described above, steel chemistry. In the former case, hold time sensitivity results suggest a larger electrode diameter-to-gauge ratio (promoting an increased cooling rate) promotes increased cracking.

Mechanistically, solidification cracking is related to the local thermal conditions, the type and level of alloy addition(s) and the primary dendrite spacing. In general, the local thermal conditions affect the kinetics of solute distribution, alloying effects the level of redistribution and the primary dendrite spacing the spatial distribution of the segregation. However, the effects of these factors are often confounded; primary dendrite spacings are affected by both composition and thermal conditions, and back diffusion in the solid (affected again by local thermal conditions) can affect actual levels of segregation achieved.

This work attempts to aid in understanding solidification cracking in spot welds (and, therefore, hold time sensitivity) by examining the relationships between composition level, local thermal conditions and primary dendrite spacings. In this paper, a composite model is presented to establish these relationships. This model uses primary dendrite spacings models from the casting literature, and combines these with local thermal information taken from a numerical model for resistance spot welding. In a subsequent paper (Part II, Ref. 33), examinations of the accuracy of this model are made by direct measurement of primary dendrite spacings for sheet steels with a range of C levels and thicknesses (thermal conditions are heavily dependent on sheet thickness).

Primary Dendrite Spacings Modeling

As suggested above, the focus of the modeling in this work is to combine existing structural modeling (in this case, for primary dendrite spacings) with specific thermal modeling for resistance spot welding. These individual aspects of the modeling are considered in separate sections below.

Over the last several decades, many efforts have been made to correlate measured dendrite spacings, both primary and secondary, to solidification conditions (Refs. 17–20). Most of this work has been done on castings and, as such, is comparable to welding at relatively slow solidification rates. In general, the effort has been made to correlate dendrite spacing to the local solidification time, defined as:

\[ t_s = \frac{\Delta T_0}{G \times R} \]  

where: \( t_s \) = local solidification time; \( \Delta T_0 \) = freezing range of the alloy = \( m_(1-k)/k \) \( c_p \); \( m \) = slope of the liquidus line; \( k \) = partition ratio of the alloy; \( c_p \) = bulk concentration of solute; \( G \) = thermal gradient in the liquid at the dendrite tips; \( R \) = solidification rate in the direction of dendrite advance.

Generally, these correlations are established graphically showing dendrite spacings as a function of \( G \times R \) on a log-log plot. Other work, however, has found
primary dendrite spacing (again on log-log plots) to be a function of \( G \times R^{1/2} \) (Refs. 19, 20).

Recently, attempts have been made to actually model primary dendrite spacings as a function of solidification conditions and alloy composition. One of these approaches has been detailed in the work of Hunt (Ref. 21). Hunt has developed a relatively intricate model for binary alloy systems based on two premises: 1) Sheil-type redistribution of solute due to dendrite thickening; and 2) a tip geometry based on a summing of undercoolings (compositional, thermal, kinetic) at the dendrite tip. The resulting expression is as follows:

\[
d = \left( \frac{-64 D_1 \Gamma \Delta T_o}{k^2 R} \right)^{1/2}
\]

where: \( k, \Delta T, G \) and \( R \) are defined as above; \( d \) = primary dendrite spacing; \( D_1 \) = effective diffusivity of the solute in the liquid; \( \Gamma = \) Gibbs Thompson parameter \(-T_c / \alpha H / T_m = \) melting temperature; \( \alpha = \) liquid-solid surface energy; \( H = \) heat of fusion.

The model itself suggests relationships between the primary dendrite spacing and both solidification conditions and alloy composition. With respect to solidification conditions, this model provides justification to the commonly used parameter \( G \times R^{1/2} \) as a measure of primary dendrite spacing. With respect to solidification, the suggestion here is that increased alloy content of a specific type will increase the primary dendrite spacing. In addition, the model presents a term, \( (\Delta T_o) \), which allows the effects of different alloys to be compared.

**The Kurz and Fisher Model**

The main drawback of the work conducted by Hunt was the assumption associated with determining the undercooling at the dendrite tip. Particularly, the morphological stability of the tip was not taken into consideration. Kurz and Fisher have conducted an alternate analysis based primarily on assessment of the critical curvature for assuring stability of the advancing dendrite tip (Ref. 22). Their analysis was also based on solidification of dilute binary alloys. The approach was first to estimate, based on a calculated diffusion field ahead of the dendrite tips and the morphological stability criterion developed by Mullins and Sekerka (Ref. 23), the wavelength of a stable perturbation. This was then assumed to be the radius of the dendrite tip. Primary dendrite spacing was then estimated by assuming the dendrite to have an elliptical longitudinal cross-section, with a major axis length equal to twice the freezing range divided by the thermal gradient. Due to the complexities of the solution for the morphological stability analysis, two models were produced, one for slow-solidification velocities and the other for high-solidification velocities. With respect to welding, the solution for high-solidification velocities is undoubtedly the most applicable. This has the following form:

\[
d = \left( \frac{36 \pi^2 D_1 \Gamma \Delta T_o}{k G^2 R} \right)^{1/2}
\]

Definitions of the terms in this model are the same as those described for the Hunt model above. In general, the relationships described by these two models are quite similar. In both cases, the prediction is that the primary dendrite spacing is a function of \( G \times R^{1/2} \). Also, both predict that the primary dendrite spacing will increase proportional to \( c_{194} \). However, there is a major difference with regard to the effects of solute type. This is shown by the differing dependence of the primary dendrite spacing on the partition ratio \( k \). The Hunt model suggests that the primary dendrite spacings are a function of \( (\Delta T_o) \), while the Kurz and Fisher model suggests a dependence on \( (\Delta T_o) / k \).

The relative fit of these approaches was investigated in detail by Gould (Ref. 8) on binary Ti alloys containing additions of either Fe or Mo. From those results, it was quite clear that the latter expression \( (\Delta T_o / k) \) was far more effective at estimating the effects of the different solute types, strongly supporting the Kurz and Fisher approach.

**Modeling Solidification Conditions in Resistance Spot Welds**

Extensive work is available on the thermal modeling of resistors in solidification quality. This work ranges from closed-form solutions (Refs. 24), one-dimensional finite difference approaches (Refs. 25–27), axisymmetric finite difference approaches coupling the current field and thermal field problems (Refs. 28–30) and, finally, axisymmetric finite element solutions also including issues of material deformation (Refs. 31, 32). Most of the numerical approaches have incorporated temperature-dependent thermal, electrical and, where appropriate, mechanical properties and, in general, yield similar results. Three areas where these models have been found to differ have been in their treatment of the latent heat of fusion, thermal response of the contact resistance and convection in the liquid pool. Two basic approaches appear to be used for incorporating the latent heat of fusion. These include isothermal introduction of the latent heat and a progressive application of the latent heat over the freezing range. The effects of using these different approaches appears to be small. How the breakdown of contact resistance is considered, however, has a large effect on the model results. Many models choose not to consider the contact resistance at all. For materials of low bulk resistivity this can introduce considerable errors in the model, so application of such models is generally restricted to higher resistivity materials such as stainless steel and Ni-based alloys (Refs. 31, 32). Temperature-dependent contact resistances were first considered in work by Gould (Ref. 27). In lieu of experimental data on the effect of temperature on contact resistance, a linear approximation was used. More recent work suggests that there is an inverse-asymptotic relationship between contact resistance and temperature, and this has been incorporated into some models (Ref. 29). Interestingly, most models do not consider convection in the liquid. As a result, many of these models predict very high temperatures in the weld pool. Those models which do consider convection in the liquid do so by assuming an enhanced heat transfer coefficient in the liquid (Refs. 26–31). Generally, an increase in heat transfer coefficient from solid to liquid between seven to ten is assumed. The effect of this enhanced heat transfer coefficient is to "flatten out" the temperature profile in the liquid, reducing the degree of superheat predicted in the liquid nugget.

**Details of the Current Approach**

In this work, the model previously developed by the author (Ref. 27) was used to predict dynamic solidification conditions. This model is a one-dimensional approach, utilizing temperature-dependent thermal and electrical properties. This model also includes the effects of electrode geometry. Convection in the liquid is incorporated by the enhanced heat transfer coefficient approach (an increase of a factor of seven on melting is assumed), and the temperature effect on contact resistance is considered using the linear assumption. This assumption is shown graphically in Fig. 1. Basically, it is assumed that the contact resistance is the measured value at room temperature, and zero at the melting temperature. Values in between these extremes are calculated based on the linear assumption. In practice, this does not appear to be a bad assumption, as the contact surface appears to reach 80 to 90% of the melting temperature within the first one or two cycles (16–32 ms). Geometric con-
Fig. 1 — Graphical representation of the assumed variation in contact resistance at the faying surface as a function of temperature used in the current model.

Fig. 2 — Geometric layout of the finite difference model used in this study.

The geometric layout of the finite difference model is shown in Fig. 2. In the steel itself, circular plate elements are employed, while truncated cone elements are used for the electrodes. The heat of fusion is added to the model isothermally.

Accuracy of this model was considered extensively in the previous work (Ref. 27). In this application, the resolution of the model for predicting solidification conditions was considered adequate for two reasons. First, both heat flow and solidification are nominally parallel to the axis of the electrodes. Second, the primary dendrite spacings models to be used contain numerous assumptions, and probably would not benefit from a more accurate thermal model.

Details of the model are available in the previous work (Ref. 27). The only major change was to increase the number of elements in each steel sheet from 10 to 20. This was done for two reasons. The first was to reduce the degree of ripple in the predicted temperatures associated with the isothermal addition of the heat of fusion, either on melting or on freezing. The second was to increase the resolution of the actual solidification conditions predicted.

The primary solidification features of interest include the solidification rate, the thermal gradient in the solid in the vicinity of the dendrite tips, and the degree of penetration of the weld nugget. Dynamic penetrations and solidification rates were calculated directly from the position of the solid-liquid interface as a function of time. Thermal gradients at the dendrite tips were assumed to be represented by the thermal gradients in the solid at the solid-liquid interface. Reasons for this were twofold. First, given the high effective heat transfer coefficient used in the liquid and the isothermal method by which the heat of fusion was introduced or removed during melting, estimated thermal gradients in the liquid during solidification were nearly always zero. Second, it was felt that the mushy zone, with limited interdendritic convection, would have heat transfer characteristics better represented by those predicted for the solid.

As mentioned above, previous work indicated errors associated with this model, particularly in heavier section materials. These errors typically manifested themselves as increased necessary currents (in experiment) to form a weld of a specific size. The reason for this appeared to be loss of heat to the surrounding sheet. In this application, however, it was felt that the additional latent heat associated with the surrounding sheet material would not adversely affect solidification rates and thermal gradients in resolidifying weld nuggets provided that the welds themselves were of a defined size. As such, in this program, when the model was used to estimate solidification conditions of an actual weld under experimental investigation, the current level of the model was adjusted to match the observed nugget size to the predicted nugget size.

Predictions of Solidification Conditions for the Various Thicknesses

As described above, the one-dimensional model was used to estimate solidification conditions for test samples made. In order to minimize errors in the predicted solidification conditions, inputs to the model were modified in two ways. The first was to use half the final thickness of the joint as the sheet thickness in the model. The second has already been described; to adjust the current in the model to exactly match the measured penetrations in each of the welds. Both of these adjustments were made under the same assumption: the critical event was the cooling of the weld. During cooling, the measured weld thicknesses and nugget penetrations were clearly the features controlling the solidification conditions. Sheet thicknesses and welding conditions for the weld studies are presented in Table 1.

Based on the assumptions described above, nugget penetration, (melting and)
solidification rates and thermal gradients in the solid through the welding cycle were calculated for each of the samples (material and thickness) examined. Some examples of these results are presented in Figs. 3 to 5. These particular examples are all with respect to a 0.5C-0.3Mn steel at three different gauges.

Generically, the three sets of curves are quite similar. The curves showing the fraction penetration as a function of time are shown in Figs. 3A, 4A and 5A for the 0.8-, 1.25- and 2.0-mm (0.030-, 0.050- and 0.080-in.) thick materials, respectively. These curves have, as described above, all been adjusted such that the peak penetration shown matches the peak penetration observed on the metallurgical cross-sections.

The variations in solidification rates for these three thicknesses of steel are shown in Figs. 3B, 4B and 5B, respectively. On these curves, positive solidification velocities are defined (arbitrarily) as melting, and negative solidification velocities are defined as resolidification. Interestingly, for all of these welds, melting velocities are relatively uniform over the duration of nugget growth. The only exceptions appear to be an initial transient at the beginning of nugget growth, and a reduction in the melting rate toward the end of the growth cycle. The initial transient is probably the result of the relatively shallow thermal gradients in the solid prior to first melting. As a related event, the reduction in melting rate at the end of the heating cycle is indicative of the progressively increasing thermal gradients in the solid as the solid-liquid interface approaches the water-cooled electrodes. Also of interest, the apparently steady-state melting rate appears to be relatively similar for the three gauges of steel examined, at roughly 5 to 8 mm/s (0.20-0.32 in./s). In contrast to the melting velocities observed, solidification velocities appear to show a wide variation over the duration of the solidification cycle. Solidification velocities are always highest immediately following termination of the welding current, and fall almost exponentially through the solidification cycle. This effect is not surprising, as at peak penetration, the solid-liquid interface is closest to the water-cooled electrode, and experiences the greatest degree of heat loss (corresponding to the highest solidification rate). As the weld nugget solidifies, however, the solid-liquid interface becomes progressively removed from the electrode, so the rate of heat extraction decreases, and the solidification rate falls. The solidification rates achieved, as well as the severity of the variation in solidification rates appears to be a strong function of gauge. Essentially, the lighter the gauge of the material, the greater both the solidification rate and the severity of change in the solidification rate through the solidification cycle.

The temperature gradient in the solid at the solid-liquid interface for these welds is presented in Figs. 3C to 5C. As described previously, the temperature gradient in the solid was of interest as it has been assumed that for the modeling
conducted here it most closely represents the thermal gradient immediately at the dendrite tips during solidification. In all cases, during melting the thermal gradient appears to increase in an almost linear fashion. Immediately following the termination in welding current, there is a drop in the thermal gradient apparently at a rate similar to the rate of increase during melting. A comparison with the weld penetration results indicates that this stage in the thermal cycle corresponds to thermal equilibration of the weld pool prior to actual solidification. When solidification actually begins, there is a sudden drop in the thermal gradient. This is believed to result from the progressive liberation of the heat of fusion from the weld pool. As solidification proceeds, the thermal gradient continues to drop, although at a progressively reducing rate. This, of course, is largely a function of the increasing distance from the solid-liquid interface to the electrodes as solidification proceeds.

Variations in gauge affected the variation in the thermal gradient in terms of the magnitudes of the thermal gradients achieved and the severity of the cycle. Peak thermal gradients varied from a value of about 2600°C/mm for the 0.8-mm (0.030-in.) thick material to about 900°C/mm for the 2.0-mm (0.080-in.) material. The variation in thermal gradient during actual solidification followed a similar pattern, with the lightest and heaviest gauge materials showing the most and least severe variations, respectively.

The results presented above can be used to calculate the variation in the groupings of solidification conditions important to understanding variations in the primary dendrite spacings. To this end, variations in the two groupings of interest (G x R and G x R^{1/2}) are presented for welds made on the three gauges of the 0.5C-0.3Mn steel in Figs. 6 to 8. With respect to the primary dendrite spacings modeling presented above, the primary term of interest is G x R^{1/2}; however, the variation in G x R is also examined for comparative purposes. In Figs. 3-5 presented above, the thermal gradient and the solidification rate both decreased nearly exponentially as a function of time during solidification. Not surprisingly then, the product of two, whether expressed as G x R or G x R^{1/2} appears to show a similar, although more radical, variation over the solidification time. The curves of G x R and G x R^{1/2} do appear quite similar, apparently largely differing only in the range of the y-scale. Notable variations did occur in these sets of curves as a function of the sheet thickness. Estimated values for the three gauges of steels included 1600°-6700°C/(mm-s)^{1/2} for the 0.8-mm (0.030-in.) steel, 900°-4400°C/(mm-s)^{1/2} for the 1.25-mm (0.050-in.) steel and 500°-1700°C/(mm-s)^{1/2} for the 2.0-mm (0.080-in.) steel.

These results indicate clearly that solidification conditions and, particularly, the grouping of solidification conditions of interest, varies considerably over the period of solidification.

**Influence of Spot Weld Conditions on Primary Dendrite Spacings**

Using the Kurz-Fisher analysis, and the solidification results obtained from the numerical thermal model, it is possible to make some estimations of the relative effects of sheet thickness and fraction solidification on the primary dendrite spacings in spot welds. For these estimations, a normalized dendrite spacings term is used. This normalized spacings term is defined as follows:

$$d_n = d \left( \frac{k}{36 \pi^2 D_1 \Gamma \Delta T_a} \right)^{1/4}$$

where $d_n$ and $d$ are the normalized and actual dendrite spacings, respectively, and the other terms are as defined previously. Effectively, the normalized dendrite spacings term accounts for material and dendrite geometry effects.

Normalized primary dendrite spacings as a function of solidification time for each of the three gauges of steel considered are presented in Fig. 9. These results show that the primary dendrite spacing increases with increasing gauge,
though for the gauges studied there is considerable overlap. This is not surprising, since the heavier gauge materials invariably showed slower solidification rates and shallower thermal gradients. Over the relative solidification periods, the primary dendrite spacing for each gauge of steel increased by a factor of 1.5 to 2. This is indicative of the steeper thermal gradients and higher solidification rates early in the resolidification of the weld nugget.

Conclusions

In this paper, a method for modeling primary dendrite spacings in resistance spot welds through a combination of numerical process modeling and existing structural development modeling has been described. Numerical thermal modeling of the resistance spot welding process was used to estimate solidification conditions in resistance spot welds. These solidification results could then be used with existing closed-form primary dendrite spacings models to predict spacings in spot welds. Correlations of these results with primary dendrite spacings measurements made on actual spot welds is considered in a subsequent paper. From this work, the following conclusions were drawn:

1) Numerical modeling suggests that the solidification rate and thermal gradient behind the solid-liquid interface decreases almost exponentially as solidification of the spot weld nugget progresses. As a result, even more extreme variations in the parameters $G \times R$ and $G \times R^{1/2}$ were noted.

2) Sheet gauge was found to have a very strong impact on solidification conditions in the spot weld. Heavier sheet gauges were found to decrease both solidification rates and the thermal gradient behind the solid-liquid interface.

3) Primary dendrite spacings were estimated to be a function of both gauge and relative position of the solidification front. For each gauge of steel, the finest primary dendrite spacings were suggested near the periphery of the weld nugget, increasing as solidification progressed. Increasing steel gauge suggested coarser dendrite spacings, though there was considerable overlap for the three gauges of steel studied.

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