HANDBOOK OF
STEEL INGOT SOLIDIFICATION

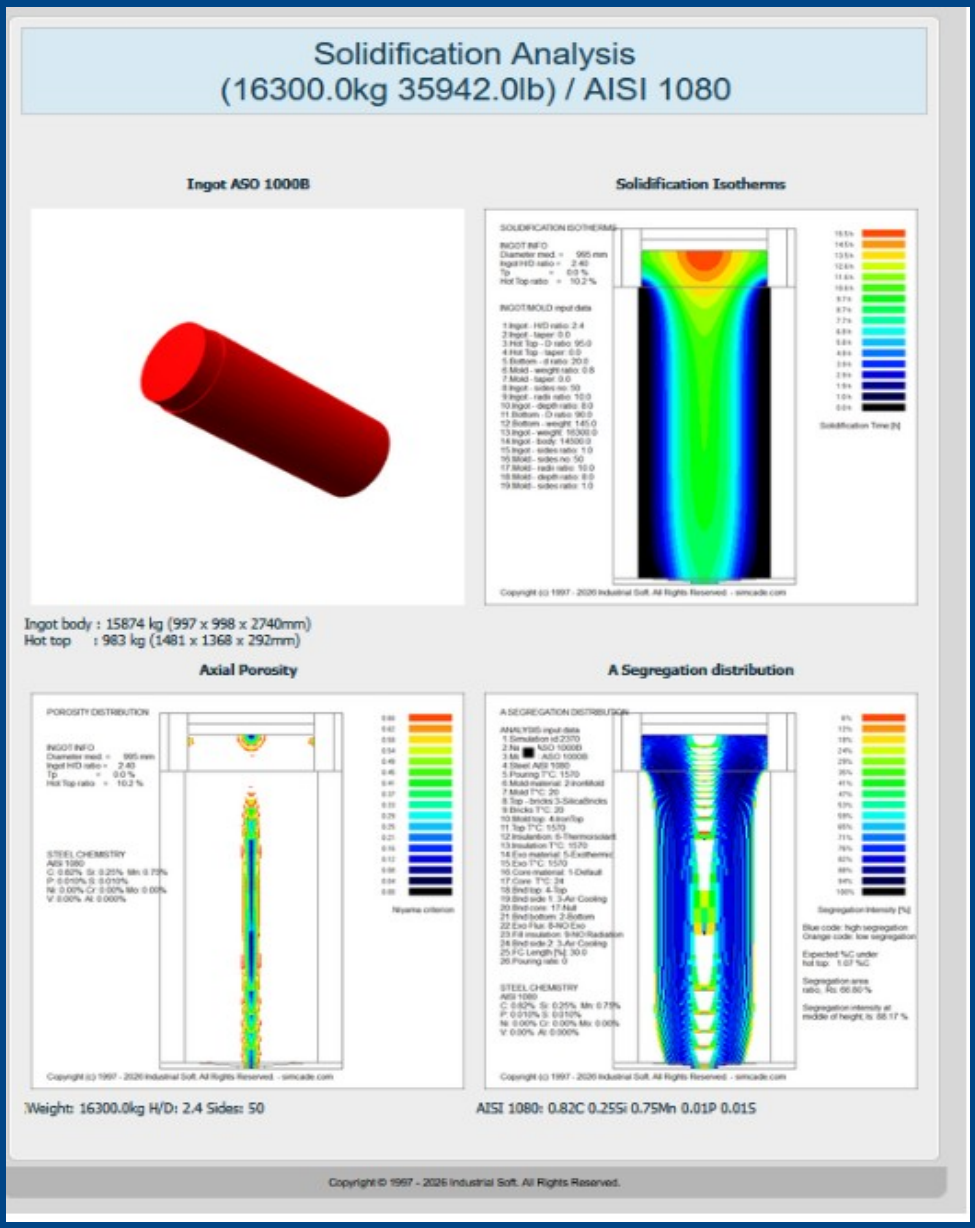
Solidification isotherms, axial porosity, A Segregation

230 Ingot Solidification Reports

Part I CARBON STEEL

AISI grades: 1008 1015 1026 1030 1045 1060 1075

Ingot size: 5.0T-10.0T (10000-20000lbs)



The internal defects that can affect the quality of steel ingots include porosity, primary and secondary pipe, positive segregation, negative segregation, V-segregation and A-segregation. From all these kind of defects, in this handbook, we are focused on porosity and A-segregation. Because these defects have an important effect on the internal quality of the final product and because the ingot manufacturers have to have the right tools to choose the right ingot size and shape for a particular steel we have developed several tools that may help to get this goal.

This handbook allows quickly access to around 230 analysis reports with the solidification isotherms and position of porosity and A segregation on transversal section of the ingot.

The size of analyzed ingots is between 5.0T and 10.0T (10000-20000lbs) with various shapes (round, corrugated or rectangular) and various carbon steel AISI grades (1008, 1015, 1026, 1030, 1045, 1060, and 1075).

Every report comes with total solidification time and several quantitative parameters to easily choose the ingot size and shape function the steel grade in order to minimize the internal defects.

Table of Contents

Table of Contents **3**
Tools, Prediction Techniques and Validation **4**
1 Introduction 4
2 Ingot and mould design software 4
3 Solidification simulation software and its validation 4
3.1 Solidification simulation software 4
3.2 Validation of the simulation software 5
4 Segregation in ingots and prediction technique 6
4.1 A segregation in steel ingots 6
4.2 Segregation prediction technique 6
4.3 Validation of segregation prediction technique 8
5 Porosity in ingots and prediction technique 9
5.1 Porosity prediction technique 9
5.2 Validation of porosity prediction technique 10
6 References 11
Porosity and segregation analysis reports **12**
AISI 1008 13
5200.0 kg (11440.0 lb) - Breitenfeld A520 - AISI 1008 14
5470.0 kg (12034.0 lb) - Gopal 5470 R - AISI 1008 15
AISI 1015 16
5470.0 kg (12034.0 lb) - Gopal 5470 R - AISI 1015 17
AISI 1026 18
5520.0 kg (12144.0 lb) - Bous 0500 Z - AISI 1026 19
5572.0 kg (12258.4 lb) - Ellwood 18 - AISI 1026 20
AISI 1045 21
6200.0 kg (13640.0 lb) - Gopal 6200 S4 - AISI 1045 22
AISI 1060 23
5800.0 kg (12760.0 lb) - Bous 58 VK - AISI 1060 24
6100.0 kg (13420.0 lb) - Bous 0710 R - AISI 1060 25
AISI 1075 26
5800.0 kg (12760.0 lb) - Bous 58 VK - AISI 1075 27
7810.0 kg (17182.0 lb) - Bous 0600 Z - AISI 1075 28

Tools, Prediction Techniques and Validation

1 Introduction

In order to develop the tools needed to predict the internal integrity of the ingots we have employed a model to design ingot moulds, a solidification simulation software to assess the solidification process variables and criteria relations to evaluate the conditions at which the porosity and A-segregation occur.

2 Ingot and mould design software

Ingot and Mould Design Assistant v.1.0 [1] is a tool based on a mathematical model that allows to design ingot and moulds using minimum data such as weight and ingot shape defined by H/D ratio, taper and number of sides. This tool can generate quickly ingot and mould projects for conventional and hollow ingots having round, rectangular or polygonal section and makes available instantly 2D drawings, 3D models, and prepare the geometrical data needed by the solidification simulation software.

In Figure 1 there are several examples of 3D models generated by Ingot Mould Design Assistant.

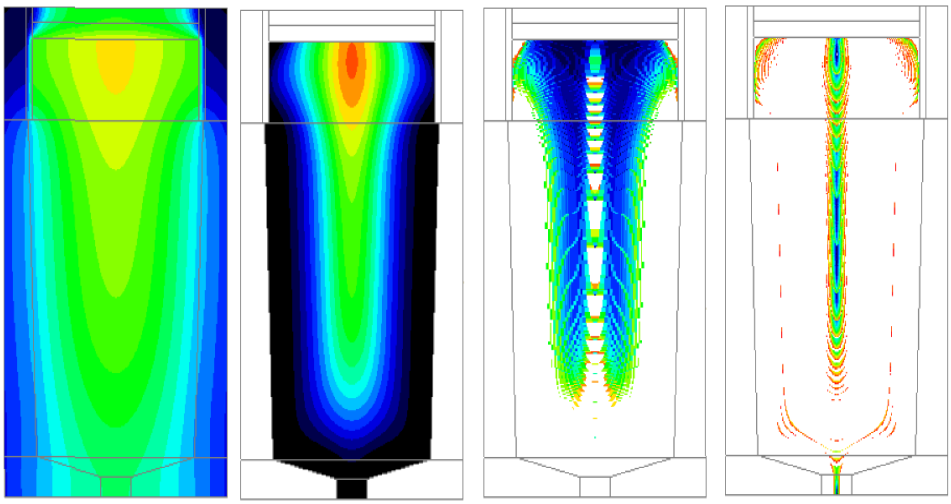


Figure 1. Ingot and moulds generated by online Ingot Mould Design Assistant

3 Solidification simulation software and its validation

3.1 Solidification simulation software

The solidification simulation software, SimCADE v.2.0 [2], takes into account the material properties, internal sources and their variation with temperature, heat exchange with the environment, insulation and exothermic materials.



a. Temperatures b. Isosolidus c. A Segregation d. Axial Porosity

Figure 2. Data generated by the solidification simulation software

The needed time to compose the problem and get the results is about 20 min. to complete the experiment and display results, Figure 2.

3.2 Validation of the simulation software

To validate the simulation software we compared the temperatures measured on the surface of a 65 tones ingot mould with the temperatures at the same points we got by simulation. From the four points of measurement, three of them have been at the level of middle bottom, ingot body and hot top and the last one on the surface of hot top.

Additionally, belong the calculated temperatures on the mould surface, in Figure 3 are presented several other temperatures, in the mould wall or in the ingot during solidification.

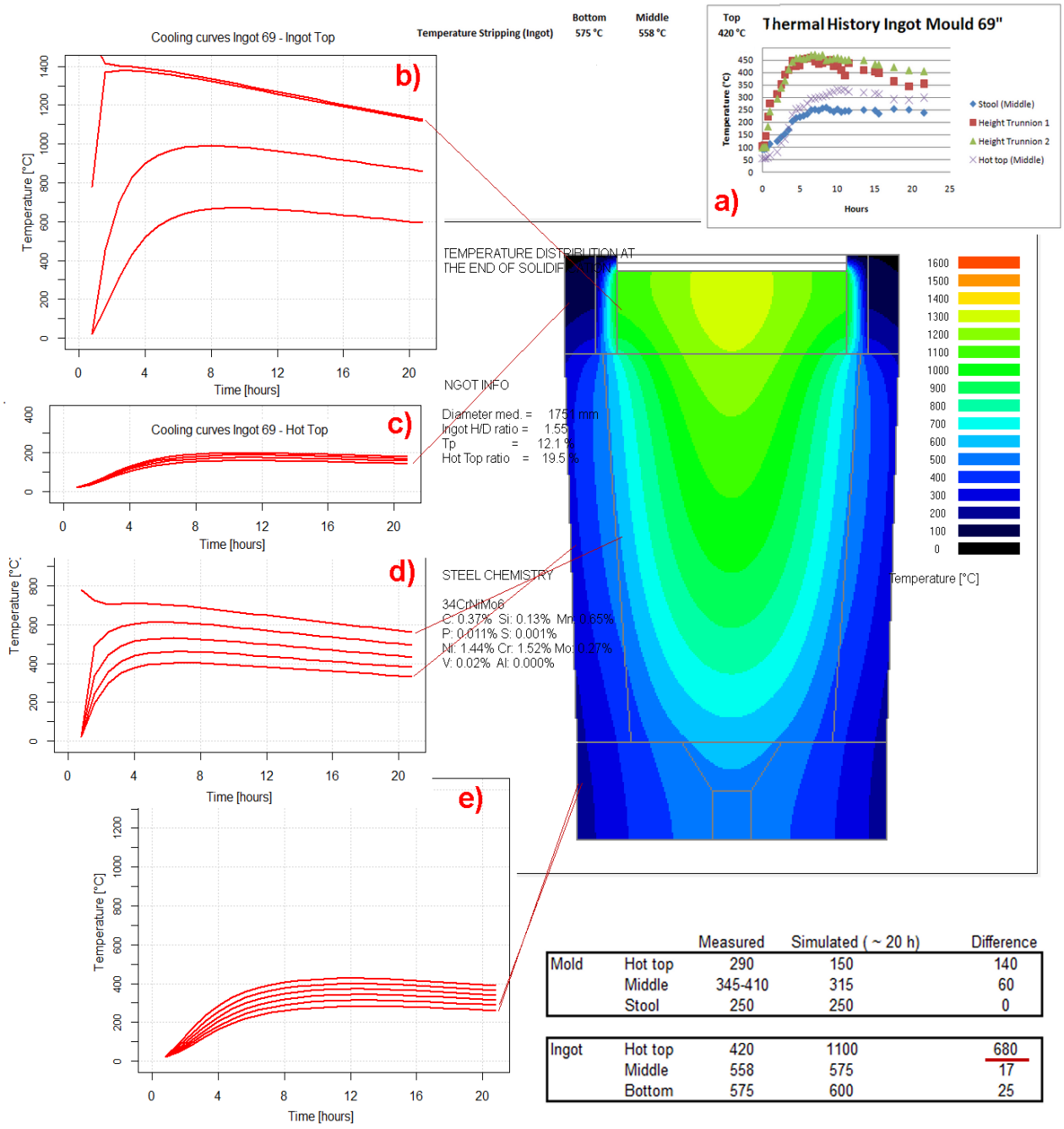


Figure 3. Validation of the solidification simulation software

As we see in this figure, the evolution of temperatures measured on the mould, Figure 3.a are in very good agreement with the calculated temperatures, Figure 3.b, 3.c, 3.d and 3.e.

4 Segregation in ingots and prediction technique

4.1 A segregation in steel ingots

Macrosegregation type commonly known as A-segregation, Figure 4, presents channels enriched by sulphur, carbon, phosphorus and is one of the factors that has a critical impact on the mechanical properties of the final forging product and one of the reasons why the forged product can be rejected at the ultrasonic test.

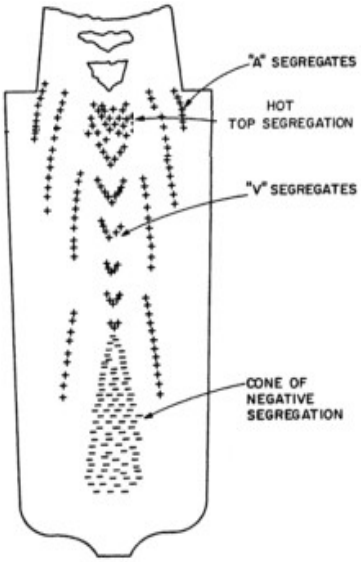


Figure 4. Macrosegregation in steel ingots [3]

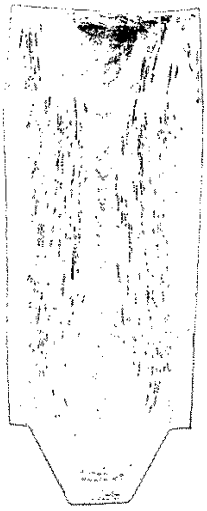


Figure 5. Sulphur print in cut ingots [7]

A-segregation forms in the zone of columnar grains at the regions with structure characterized by the transition from the columnar to large equiaxed grains and is often accompanied by porosity.

This defect is due to the shrinkage process during phase transformation combined with a simultaneous redistribution of impurities in the two-phase zone during the solidification process. The main cause of A-segregation is the relative movement of segregated liquid during solidification. Most elements have a lower solubility in solid than in liquid phase as is shown by phase diagrams. During solidification process, the solutes are rejected into the liquid phase, leading to a continual enrichment of the liquid and lower concentrations in the primary solid. By this mechanism, the size of A-segregation may be, function by solidification conditions and ingot size, from several millimetres to centimetres or even meters as shown in sectioned ingots [4], [5], [6], and Figure 5 [7]. Because of the low diffusion of the solutes in the solid state and the large distances involved, macro segregation cannot be removed after the solidification is completed.

4.2 Segregation prediction technique

The segregation in the columnar zone is much influenced by the cooling and solidification rate. To define the A-segregation occurring conditions K. Suzuki and T. Miyamoto [7] proposed the following equation, based on solidification rate R (mm/mm) and cooling rate ε (°C/min):

$\varepsilon R^{1.1} \leq \alpha$

They have investigated at Muroran Research Centre, The Japan Steel Works Ltd. (JSW) a 0.7 % carbon steel and obtained α = 8.75, the critical value of A-segregation appearance; α is a value established experimental and depends strongly by chemical composition.

Using laboratory experimental data we have developed a mathematical model to evaluate and asses the critical value α, the value at which the A-segregation starts to appear. The model takes into account the solidification limits, change in density of solutes at the solidification front and the chemical composition of the steel (C, Si, Mn, P, S, Ni, Cr, Mo and V).

At the moment our mathematical model is applicable to Cr-Mo, Ni-Mo, Ni-Cr-Mo-V, Mn-Ni-Mo and carbon steels. More experiments must to be done to cover other steels.

In Figure 6 is presented the flowchart of technique we have developed to model the A-segregation in steel ingots. In this flowchart there are two branches. The left branch calculates, by simulation, the cooling and solidification rate. This branch, that has as input data the ingot geometry taken from the ingot design software, calculates using solidification simulation software the cooling and solidification rate. The other branch calculates, using the chemical composition, the critical value α, the value at which the A-segregation will appear. Then, the software compares the values we got from both branches and plots the segregation area in regions that contain values below the critical value.

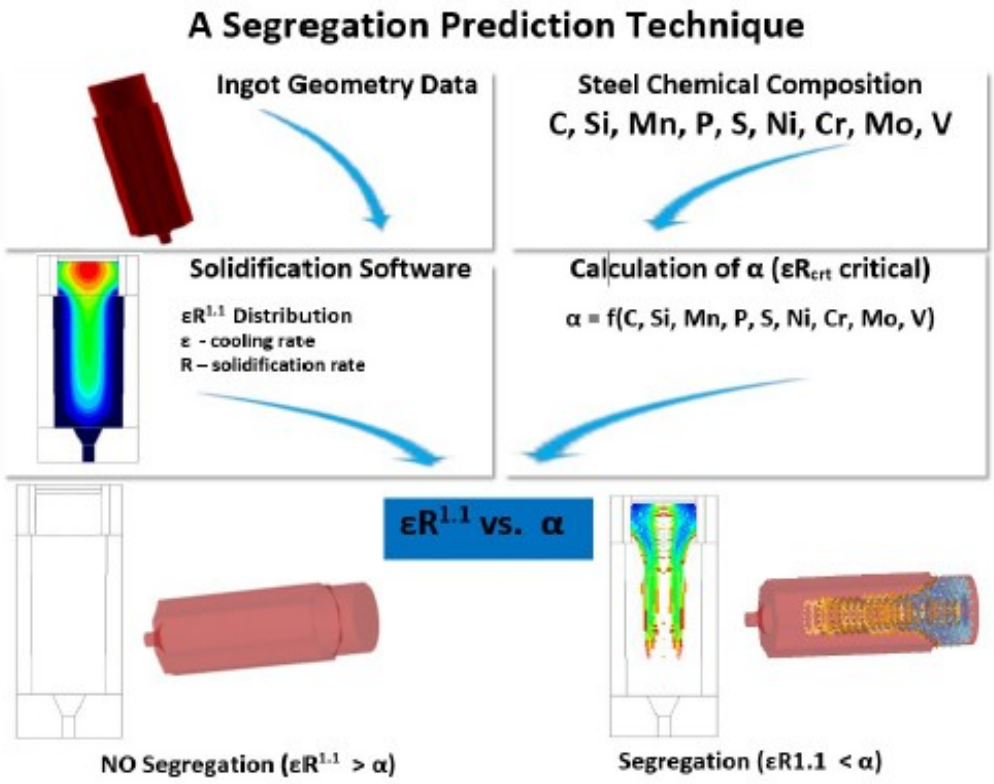


Figure 6. A-segregation prediction technique

Here, we have two situations; in the first case, if the solidification rate is bigger than the critical value α, as seen in the bottom left side example, we do not have segregation; in the second one, if the solidification rate is lower than

the critical value α, we will have A-segregation and its intensity depends on the difference between local $\varepsilon \bullet R^{1.1}$ and critical value α.

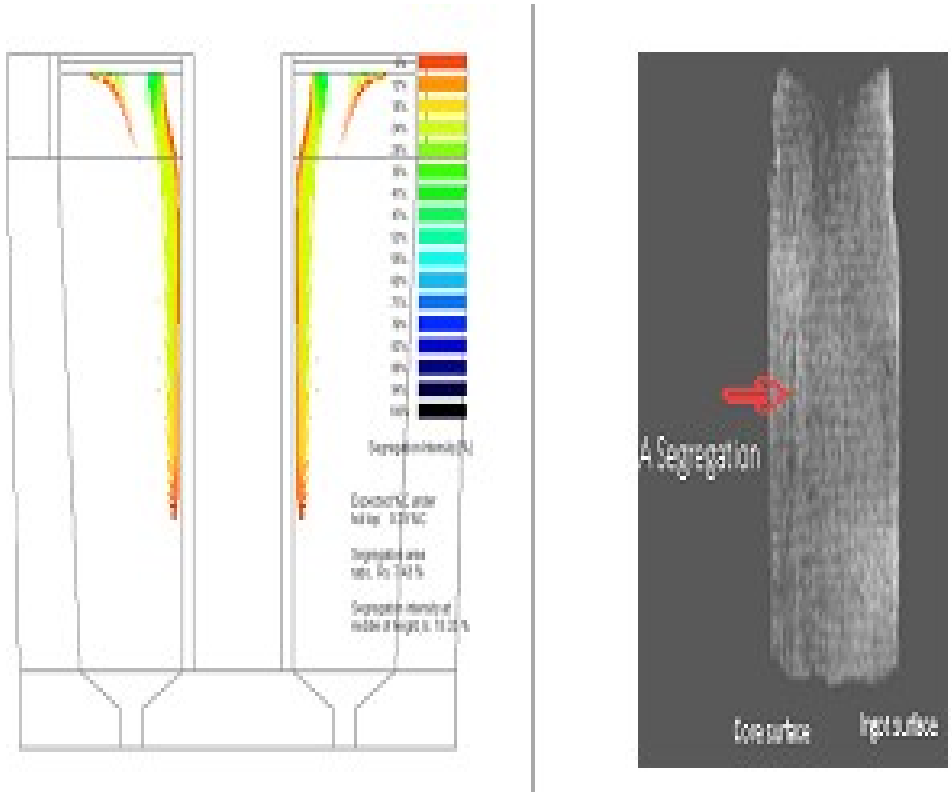
To asses quantitatively the influence of various variables on A-segregation, we have defined the parameter Rs, the ratio between area affected by A-segregation and the longitudinal section area of the ingot body.

More, because in controlling the A-segregation it is important not only the area of segregation but also the size and distribution of segregates inside the segregation area, we defined the parameter Is, Intensity of A-segregation, as difference between the critical value α and local $\varepsilon \bullet R^{1.1}$. These values will be shown in every solidification analysis report of this handbook.

4.3 Validation of segregation prediction technique

The calculation of critical value α, has been validated using both, data published in various technical papers [8], [9], [10], [11], [12], [13] and in industrial conditions with several companies using the results of ultrasonic test for over 50 ingots with weights between 5 to 220 tones.

Bellow is a validation of the segregation prediction technique made by comparing the sulphur print of a 20 tones carbon steel cut hollow ingot [11], Figure. 7.b with the segregation distribution on the transverse section we got by simulation, Figure 7.a. Please note that in Figure 7, the sulphur print is made only on a half of the ingot section.



a) A segregation simulation b) Sulphur print in cut ingot [11]

Figure 7. A segregation in carbon steel 20T hollow ingot

As we see in Figure 7, the position and size of A segregation in modelled distribution, Figure 7.a are practically the same as in the cut ingot, Figure 7.b; a good agreement between simulation and real data.

5 Porosity in ingots and prediction technique

Shrinkage porosity in forging ingots is another common defect in steel ingots and one of the reasons, besides macrosegregation, why the manufacturer has to choose the right technology to improve the internal soundness of the ingot.

A porosity distribution map may help the technology designer to choose the right casting parameters to avoid shrinkage defects in steel forging ingots. The most employed method to predict the porosity area size and its location is the following Niyama criterion:

$$Ny = \frac{G}{\sqrt{\varepsilon}} < 1$$

Ny - Niyama value
G - thermal gradient
ε - cooling rate

5.1 Porosity prediction technique

To predict the porosity area size and its location, we use the Niyama criterion, the most common criterion for porosity prediction in steel ingots. Based on previous relation, we have developed the porosity prediction technique presented in Figure 8:

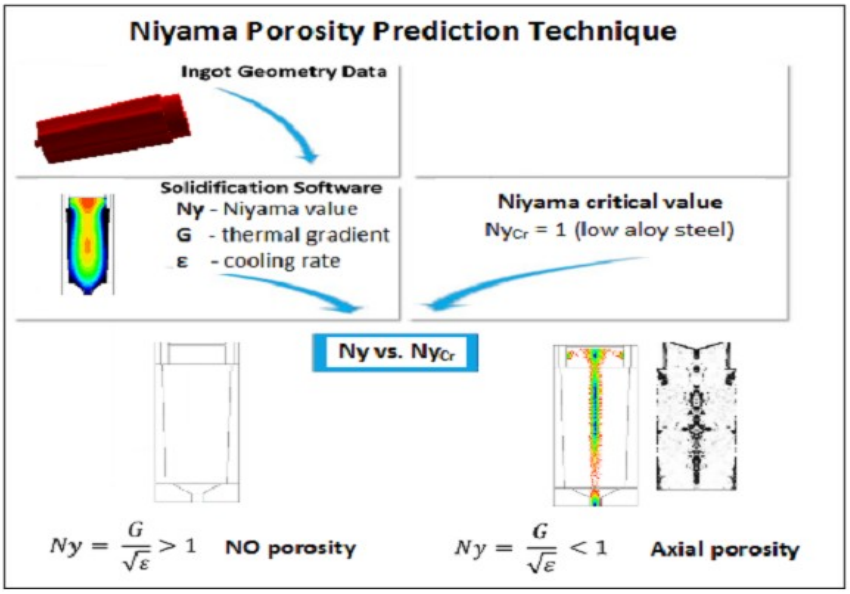


Figure 8. Axial porosity prediction technique

In this figure there are two branches:

- the left branch which calculates by simulation the temperature gradient and cooling rate has as input data the material properties and ingot geometry taken from ingot mould design software;

- in the the right branch is Niyama critical value (established experimental) at which the porosity occurs; for low alloyed steels this critical value is 1.0.

Then, the analysis software compares the values from both branches and plots the area where shrinkage porosity occurs. Here, there are two situations:

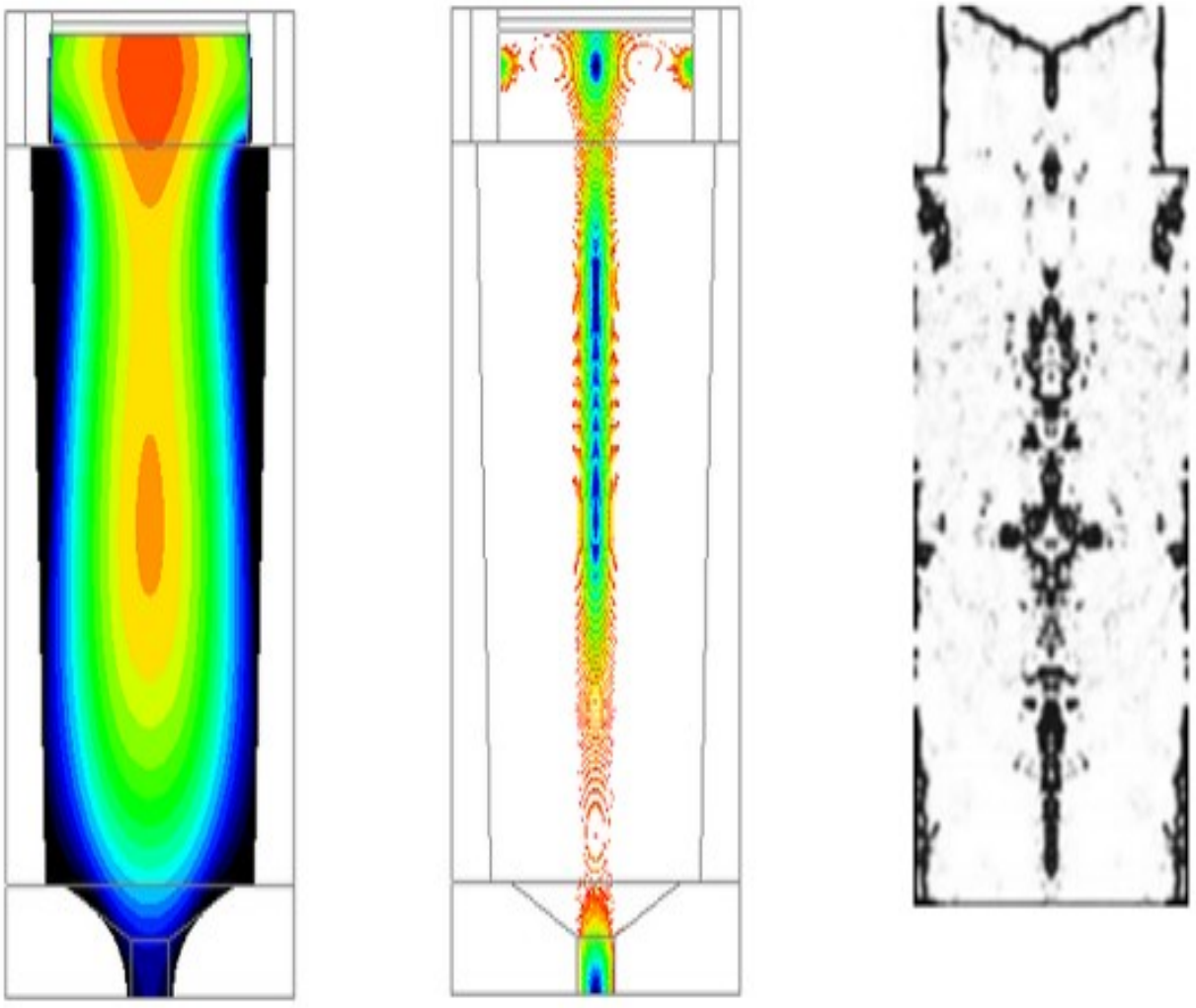
1.In the first case, if the solidification rate is lower than the Ny critical value, there will not be porosity;

2.In the second one, if the solidification rate is bigger than the Ny critical values, the shrinkage porosity occurs.

To quantitatively appreciate the influence of various variables on porosity, we use in solidification analysis the parameter Rp (porosity area ratio), the ratio between area affected by porosity and the longitudinal section of the ingot body.

5.2 Validation of porosity prediction technique

The simulation software has been validated using our experimental data and results published in [4], [5], [6]. The value of Niyama criterion and porosity module of the software has been calibrated using a cut ingot [14] as seen in the figure below:



a. Solidification isotherms b. Axial porosity c. Axial porosity in cut ingot [14]

Figure 9. Axial porosity comparison between simulation and 8T cut ingot

6 References

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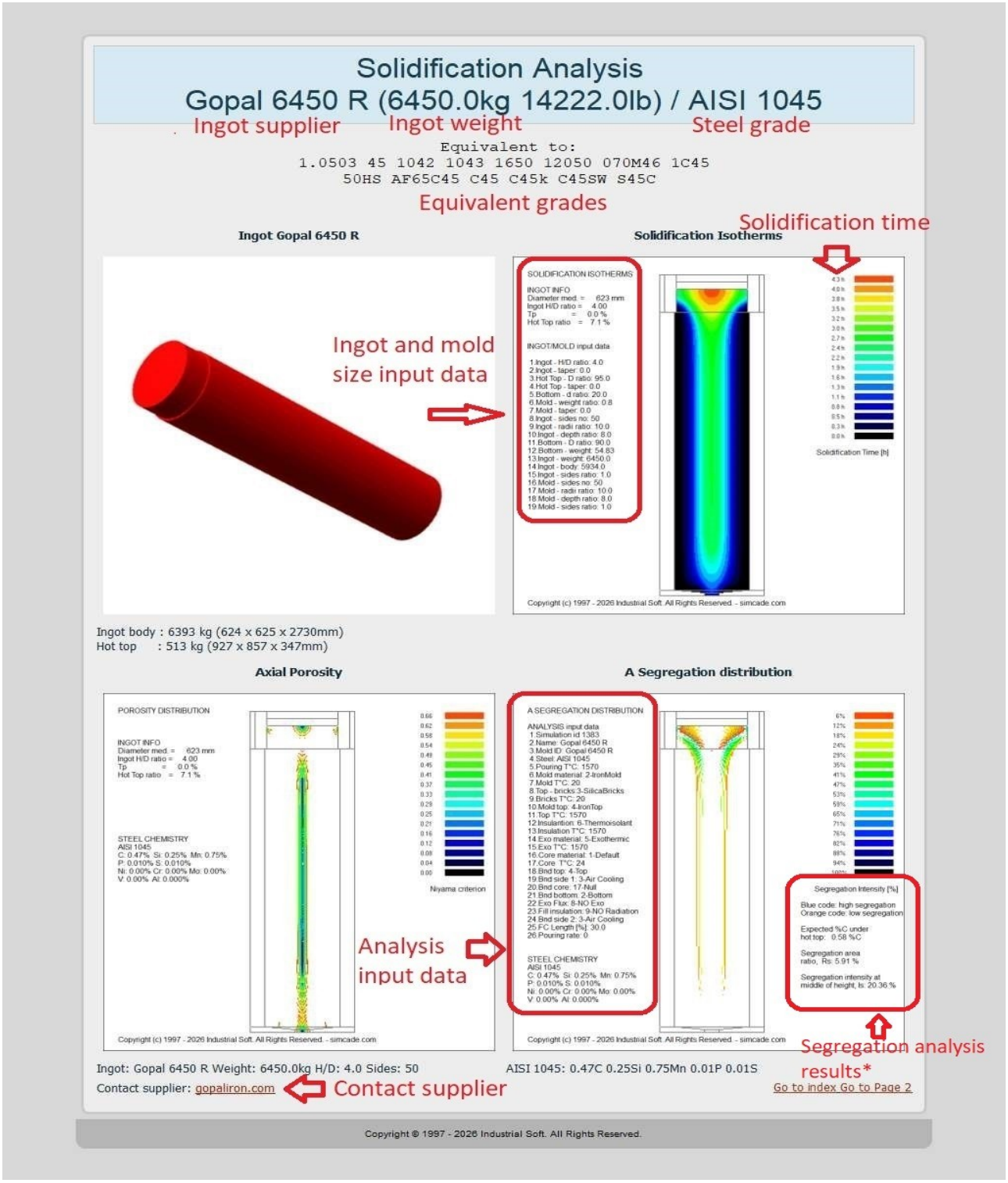
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[14] Martin Balcar et all : Developing and Testing a New Type-8k Mould For Tool-Steel Ingot Casting, Materials and Technologies 42(1):33-38 • January 2008

Porosity and segregation analysis reports



***Segregation analysis results**

Rs is the ratio between area covered by A segregation and transversal section of the ingot; **its value is useful to choose the ingot with minimum segregation, if Rs = 0, there is no segregation.**

Is – segregation intensity ratio – measures the size of the segregates at local level; a bigger value means a bigger size of segregation channels;

AISI 1008

AISI 1008 is a low-carbon, mild steel with excellent ductility, formability, and weldability, primarily used for cold-formed parts, wire, and structural components. It features < 0.10% carbon, offering high flexibility and weldability. Common applications include automotive, fasteners, and appliance components.

Composition:

Carbon: < 0.10%, Manganese: 0.30-0.50%, Phosphorus: < 0.040%, Sulfur: < 0.050%

Mechanical Properties:

Typical tensile strength around 340 MPa (49,300 psi), yield strength around 285 MPa (41,300 psi), and a Brinell hardness of 80-100 HB.

Formability: Highly suitable for cold heading, cold forging, and bending.

Weldability: Excellent, suitable for spot, projection, and butt welding.

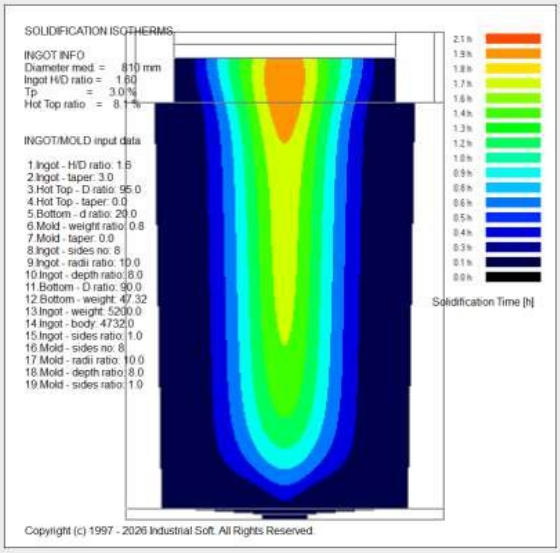
5200.0 kg (11440.0 lb) - Breitenfeld A520 - AISI 1008

Solidification Analysis
Breitenfelt A520 (5200.0kg 11466.0lb) / AISI 1008

Ingot Breitenfelt A520

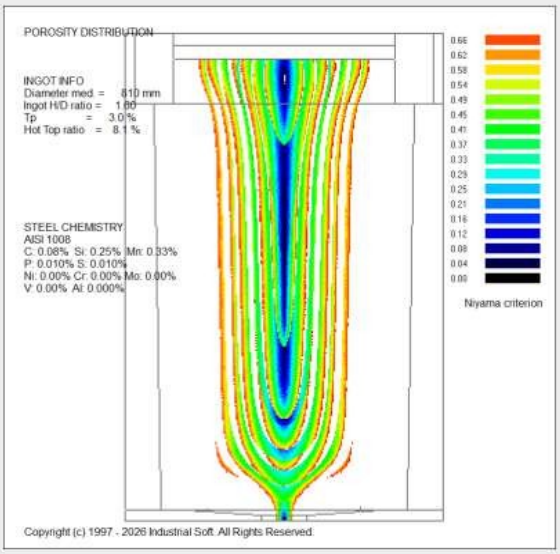


Solidification Isotherms

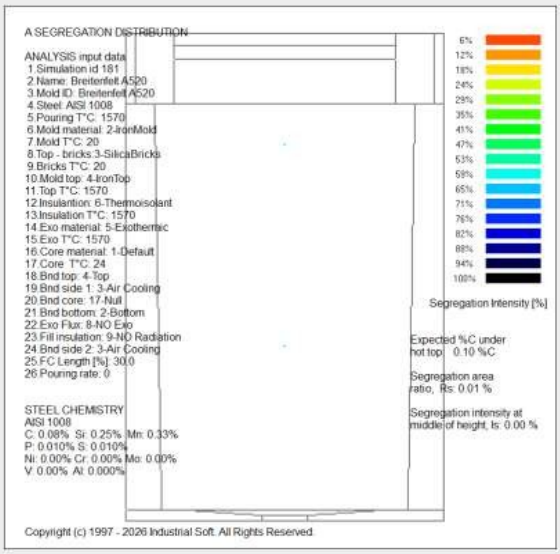


Ingot body : 4742 kg (820 x 820 x 1474mm)
Hot top : 162 kg (1090 x 999 x 130mm)

Axial Porosity



A Segregation distribution



Ingot: Breitenfelt A520 Weight: 5200.0kg H/D: 1.6 Sides: 8

AISI 1008: 0.08C 0.25Si 0.33Mn 0.01P 0.01S

Contact supplier: breitenfeld.at

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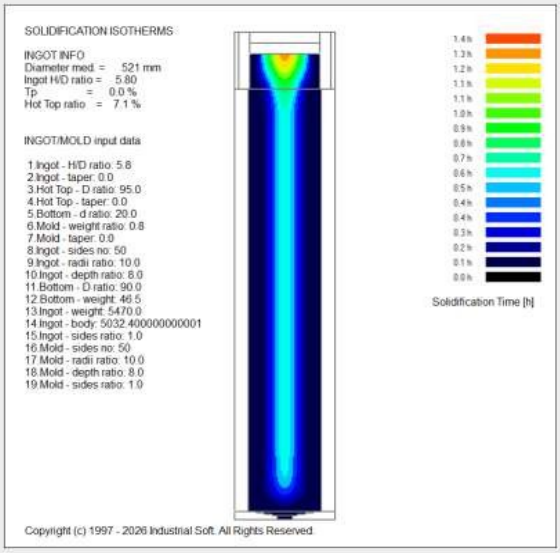
5470.0 kg (12034.0 lb) - Gopal 5470 R - AISI 1008

Solidification Analysis
Gopal 5470 R (5470.0kg 12061.0lb) / AISI 1008

Ingot Gopal 5470 R

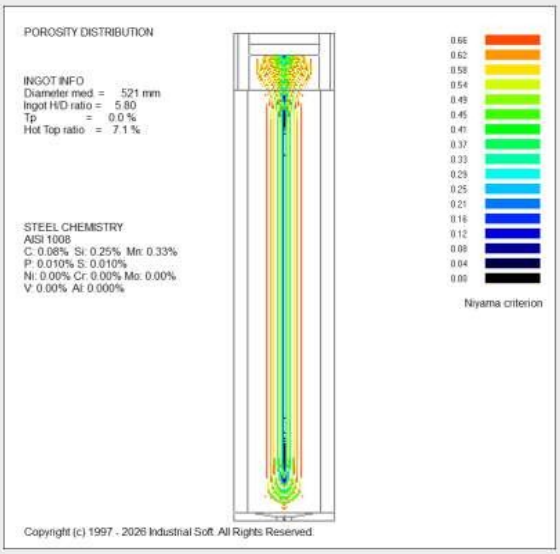


Solidification Isotherms

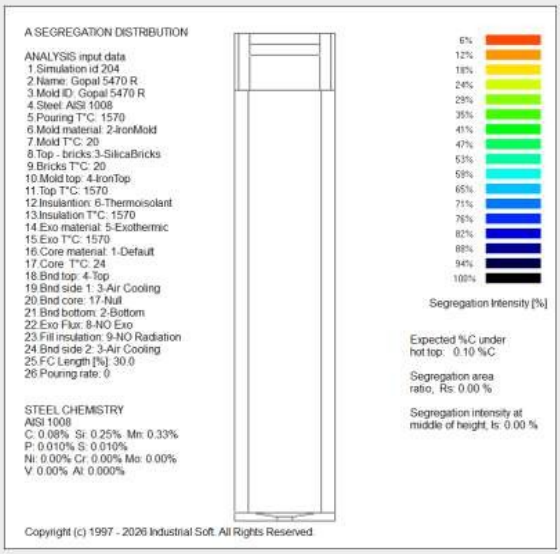


Ingot body : 5423 kg (522 x 523 x 3309mm)
Hot top : 436 kg (775 x 717 x 420mm)

Axial Porosity



A Segregation distribution



Ingot: Gopal 5470 R Weight: 5470.0kg H/D: 5.8 Sides: 50

AISI 1008: 0.08C 0.25Si 0.33Mn 0.01P 0.01S

Contact supplier: gopaliron.com

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AISI 1015

AISI 1015 is a low-carbon (mild) steel, often used for parts requiring cold forming, forging, or carburizing. It features excellent weldability, good machinability, and low strength, typically utilized in general-purpose engineering, automotive components, and structural applications. Common forms include hot-rolled, cold-drawn, or annealed, often having a tensile strength around 385 MPa.

Composition:

Carbon: 0.13 – 0.18%, Manganese: 0.30 – 0.60%, Phosphorus: < 0.040%,

Sulfur: < 0.050%

Mechanical Properties:.

Tensile Strength: 385 MPa (55800 psi), Yield Strength: 325 MPa (47100 psi),Hardness: ~111 Brinell

Common Applications:

Automotive parts (e.g., small gears, shafts), Cold-headed fasteners and rivets, general structural and engineering applications, case-hardened components (carburized).

Standard Equivalent:

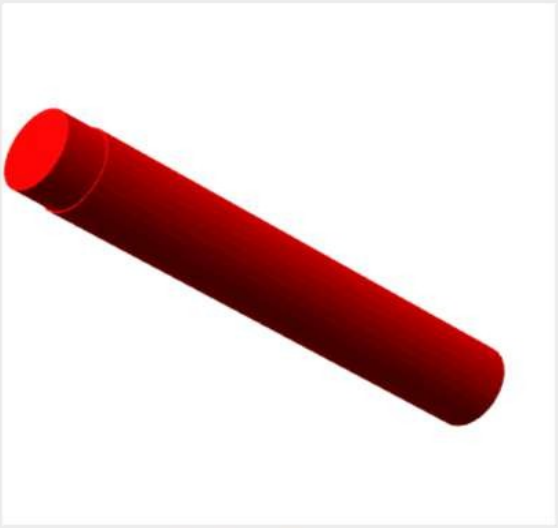
S235JR RSt37-2 St37-2 SM400A SS400 40A 40B Fe360B Fe360BFN S235JRG2 AE235B AE235B-FN Q235A Q235B Q235D 1311 1312 NS12123 St2ps St2sp St3ps St3sp E235B Fe360B IS226

5470.0 kg (12034.0 lb) - Gopal 5470 R - AISI 1015

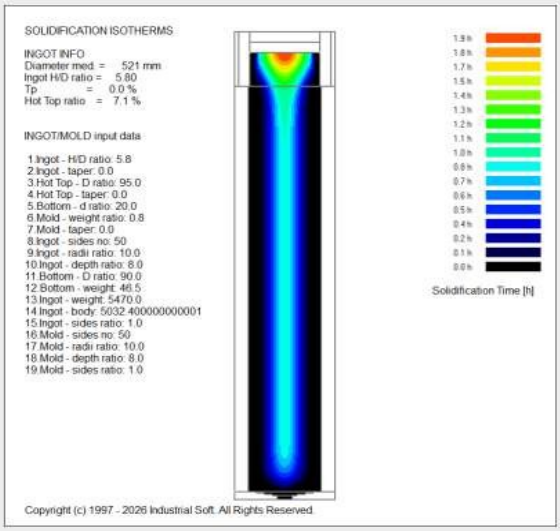
Solidification Analysis
Gopal 5470 R (5470.0kg 12061.0lb) / AISI 1015

Equivalent to:
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Q235A Q235B Q235D RSt37-2 S235JR S235JRG2 SM400A SS400
St2ps St2sp St37-2 St3ps St3sp

Ingot Gopal 5470 R

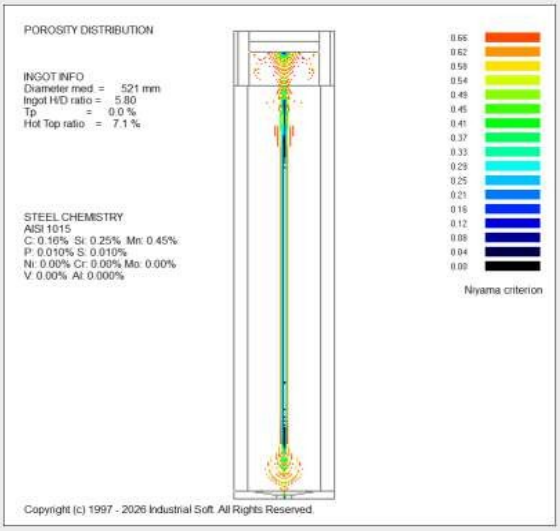


Solidification Isotherms

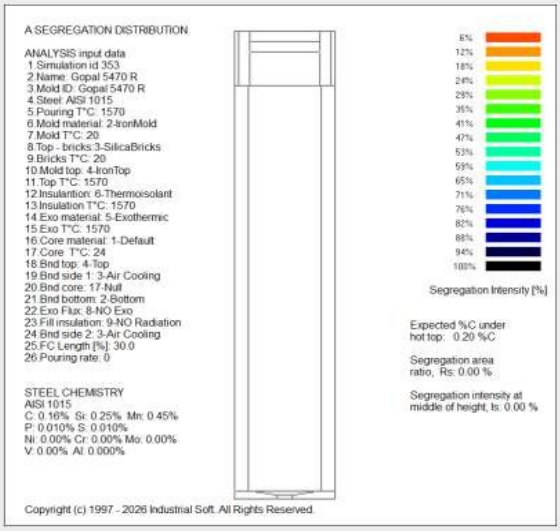


Ingot body : 5423 kg (522 x 523 x 3309mm)
Hot top : 436 kg (775 x 717 x 420mm)

Axial Porosity



A Segregation distribution



Ingot: Gopal 5470 R Weight: 5470.0kg H/D: 5.8 Sides: 50

AISI 1015: 0.16C 0.25Si 0.45Mn 0.01P 0.01S

Contact supplier: gopaliron.com

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AISI 1026

AISI 1026 is a low carbon steel (0.22-0.28% carbon) commonly used for automotive, appliance, and construction parts due to its excellent cold-forming properties. It is known for good weldability, decent strength (tensile, yield) and is widely used for structural tubing and fasteners.

Composition:

Carbon: 0.22-0.28%, Manganese: 0.60-0.90%

Mechanical Properties:

Tensile strength: ~490 MPa (71,100 psi)

Yield strength: ~415 MPa (60,200 psi).

Formability: Highly versatile; it responds well to heat treatment and is excellent for cold forming.

Common Applications: Often used for cold-drawn seamless tubing (DOM), engine parts, and hardware.

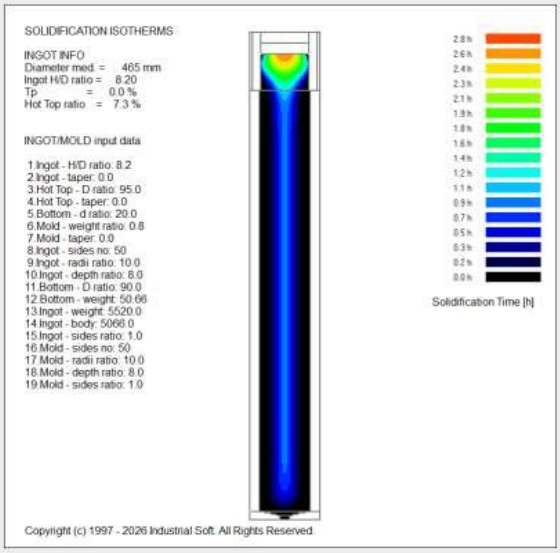
5520.0 kg (12144.0 lb) - Bous 0500 Z - AISI 1026

Solidification Analysis
Bous 0500 Z (5520.0kg 12172.0lb) / AISI 1026

Ingot Bous 0500 Z

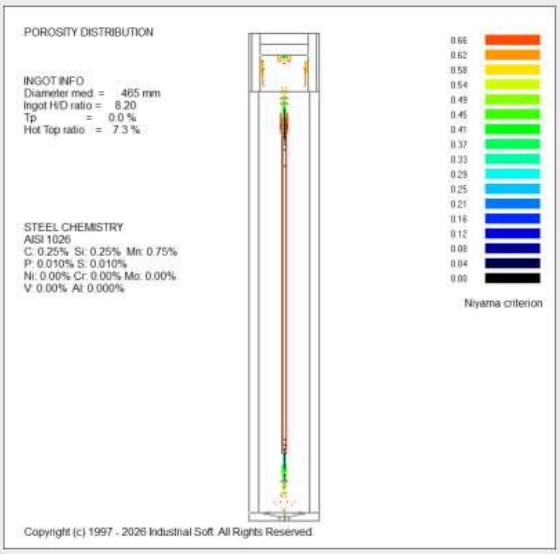


Solidification Isotherms

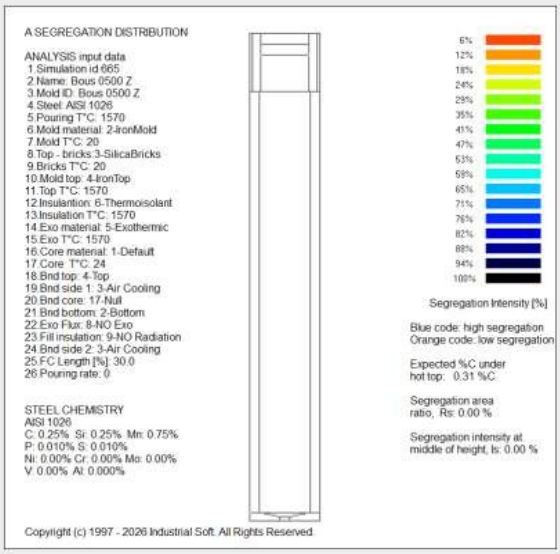


Ingot body : 5371 kg (466 x 466 x 4229mm)
Hot top : 215 kg (693 x 640 x 292mm)

Axial Porosity



A Segregation distribution



Ingot: Bous 0500 Z Weight: 5520.0kg H/D: 8.2 Sides: 50

AISI 1026: 0.25C 0.25Si 0.75Mn 0.01P 0.01S

Contact supplier: www.gmh-gruppe.de

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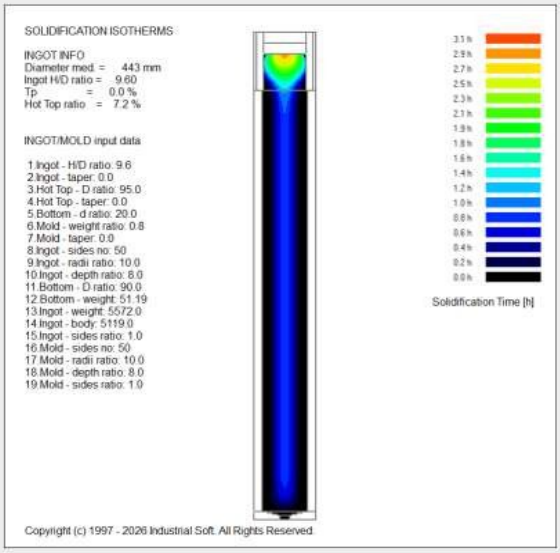
5572.0 kg (12258.4 lb) - Ellwood 18 - AISI 1026

Solidification Analysis
Ellwood 18 (5572.0kg 12286.0lb) / AISI 1026

Ingot Ellwood 18

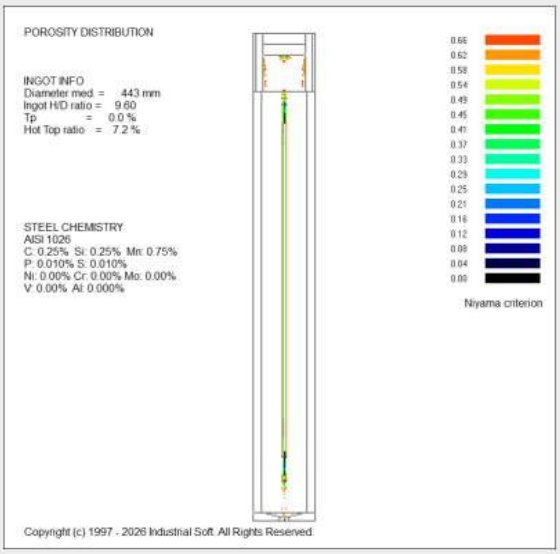


Solidification Isotherms

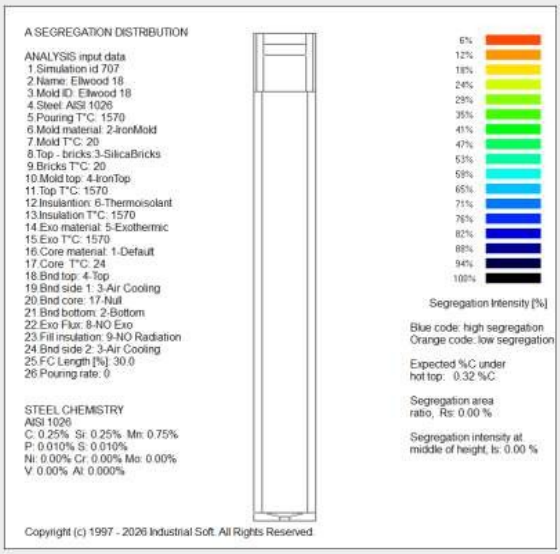


Ingot body : 5428 kg (444 x 444 x 4708mm)
Hot top : 215 kg (658 x 610 x 318mm)

Axial Porosity



A Segregation distribution



Ingot: Ellwood 18 Weight: 5572.0kg H/D: 9.6 Sides: 50

AISI 1026: 0.25C 0.25Si 0.75Mn 0.01P 0.01S

Contact supplier: www.ellwoodqualitysteels.com

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AISI 1045

AISI 1045 carbon steel is a medium-carbon steel widely used in manufacturing due to its balanced strength, machinability, and affordability.

Composition:

Carbon: 0.43-0.50%, Manganese: 0.60-0.90%, Phosphorus: < 0.040%, Sulfur: < 0.050%, Silicon: 0.15-0.35%

Mechanical Properties:

Typical tensile strength 700 MPa, yield strength 400 MPa, and a Brinell hardness of 120-220 HB

Common Applications:

Automotive: Crankshafts, axles, and connecting rods requiring high strength and impact resistance.

Machinery: Gears, shafts, and pins needing a balance of hardness and toughness.

Construction: Bolts, studs, and hydraulic rams for structural integrity.

Tooling: Blades, cutting tools, and industrial knives benefiting from wear resistance.

Agriculture: Farm machinery components exposed to high stress and abrasion.

Equivalents:

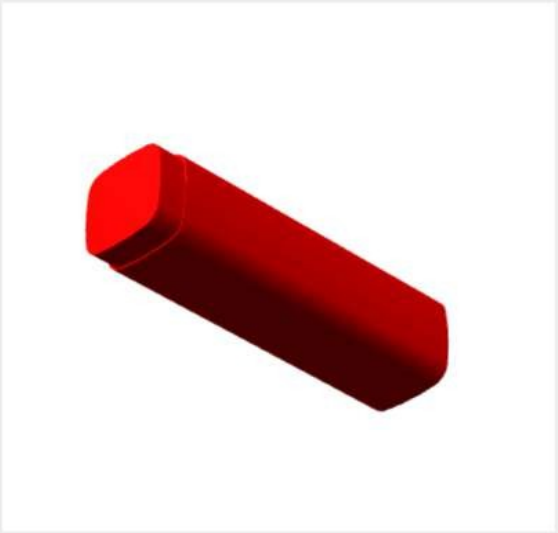
C45 1.0503 1042 1043 C45 S45C AF65C45 070M46 50HS 1C45 C45k 45 1650 12050 C45SW

6200.0 kg (13640.0 lb) - Gopal 6200 S4 - AISI 1045

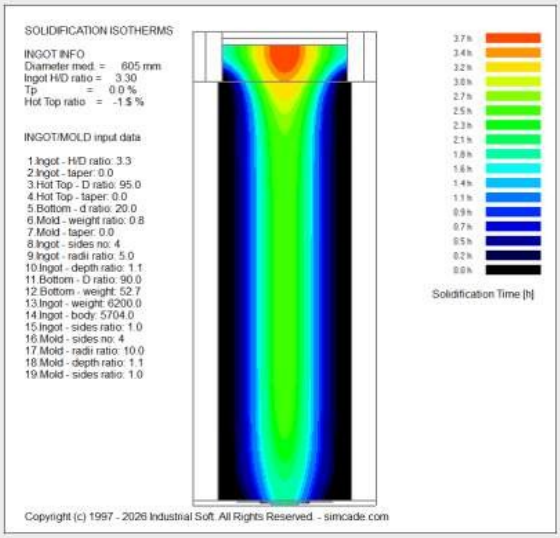
Solidification Analysis
Gopal 6200 S4 (6200.0kg 13671.0lb) / AISI 1045

Equivalent to:
1.0503 45 1042 1043 1650 12050 070M46 1C45
50HS AF65C45 C45 C45k C45SW S45C

Ingot Gopal 6200 S4

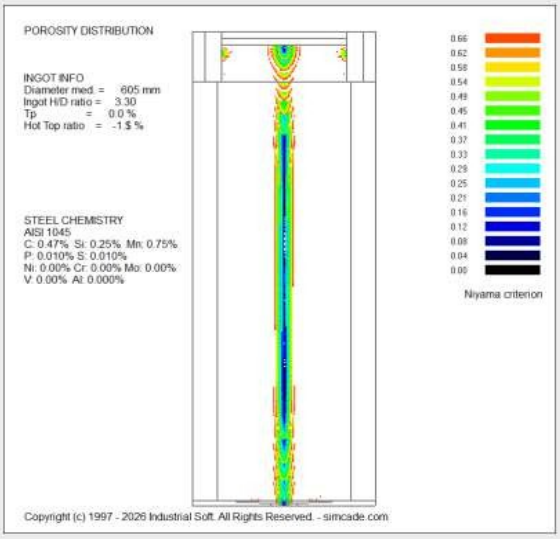


Solidification Isotherms

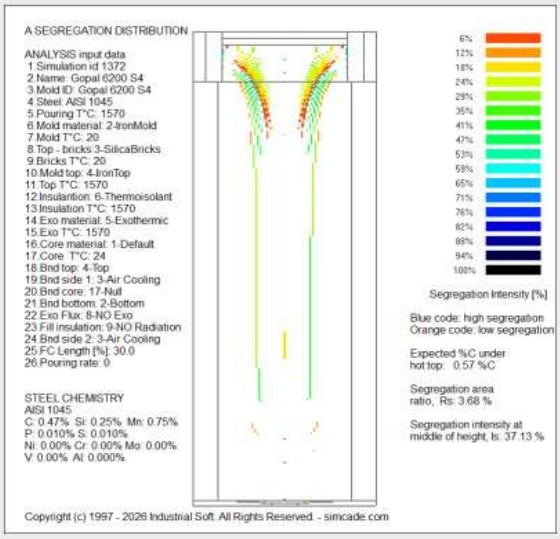


Ingot body : 5668 kg (605 x 605 x 2193mm)
Hot top : 231 kg (902 x 829 x 247mm)

Axial Porosity



A Segregation distribution



Ingot: Gopal 6200 S4 Weight: 6200.0kg H/D: 3.3 Sides: 4

AISI 1045: 0.47C 0.25Si 0.75Mn 0.01P 0.01S

Contact supplier: gopaliron.com

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AISI 1060

AISI 1060 is a high-carbon, non-alloy steel with approximately 0.60% carbon, offering high strength, wear resistance, and good, balanced toughness for applications like gears, shafts, and cutting tools. It is commonly used for machinery parts that require high strength. It requires heat treatment (oil or water quenching) to reach maximum hardness.

Composition:

Carbon: 0.55-0.65%, Manganese: 0.60-0.90%

Mechanical Properties:

Tensile Strength: 620 MPa

Yield strength: 485 MPa

Hardness: 183-255HB

Machinability:

Good in the annealed condition.

Applications:

Commonly used for agricultural tools, automotive parts, machinery shafts, high-strength springs, and bladed tools like swords or axes.

Equivalents:

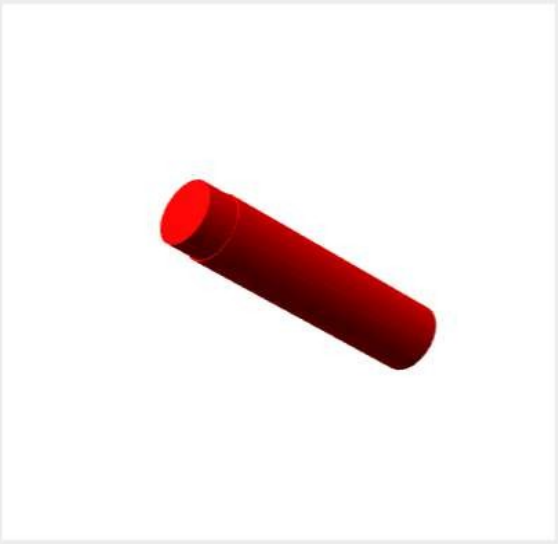
C60 1.0601 S58C 070M60 1C60 60 60G

5800.0 kg (12760.0 lb) - Bous 58 VK - AISI 1060

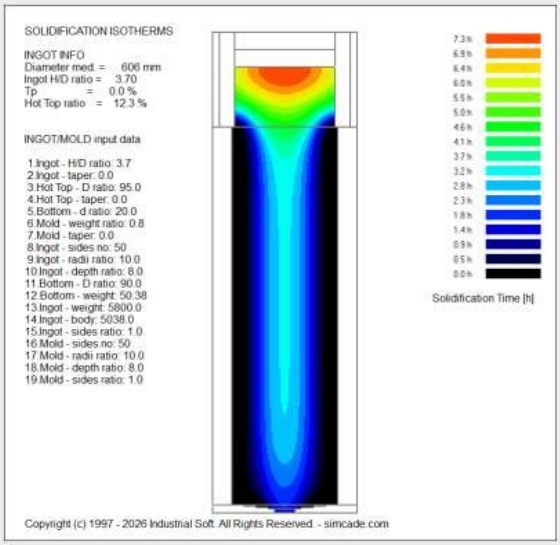
Solidification Analysis
Bous 58 VK (5800.0kg 12789.0lb) / AISI 1060

Equivalent to:
1.0601 60 070M60 1C60 60G C60 S58C

Ingot Bous 58 VK

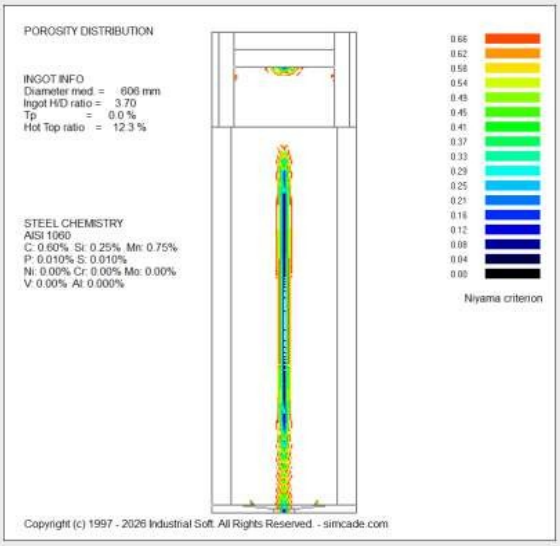


Solidification Isotherms

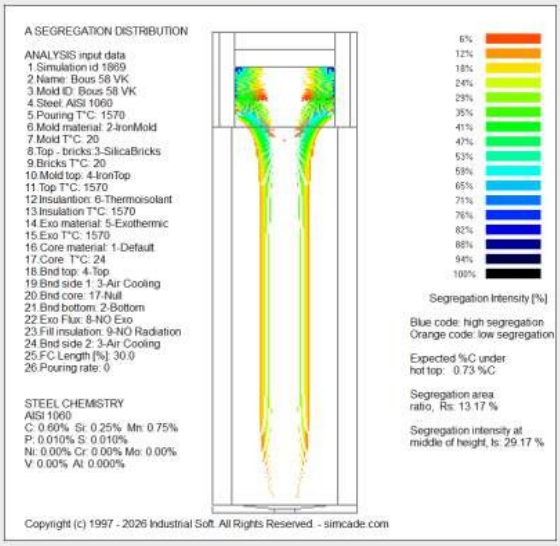


Ingot body : 5655 kg (607 x 608 x 2636mm)
Hot top : 438 kg (901 x 833 x 351mm)

Axial Porosity



A Segregation distribution



Ingot: Bous 58 VK Weight: 5800.0kg H/D: 3.7 Sides: 50

AISI 1060: 0.6C 0.25Si 0.75Mn 0.01P 0.01S

Contact supplier: www.gmh-gruppe.de

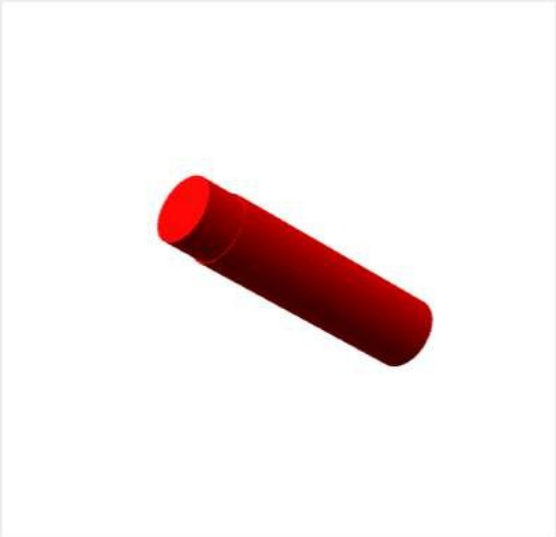
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6100.0 kg (13420.0 lb) - Bous 0710 R - AISI 1060

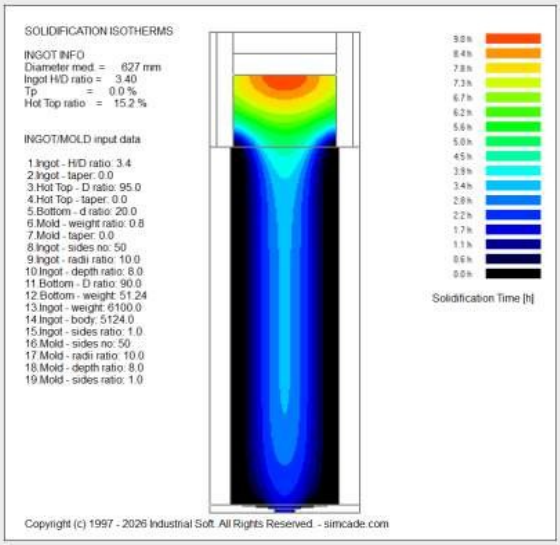
Solidification Analysis
Bous 0710 R (6100.0kg 13450.0lb) / AISI 1060

Equivalent to:
1.0601 60 070M60 1C60 60G C60 S58C

Ingot Bous 0710 R

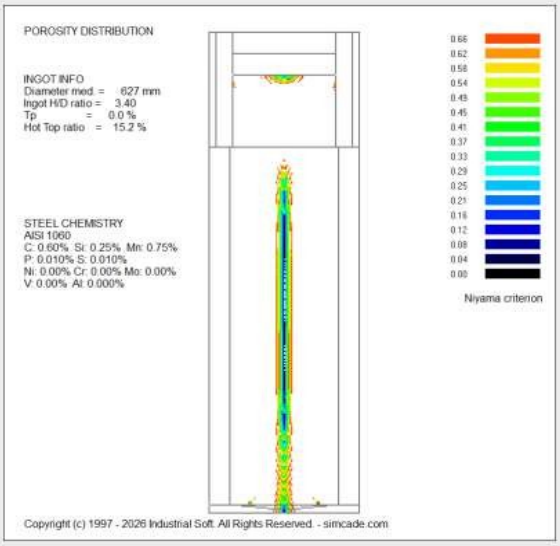


Solidification Isotherms

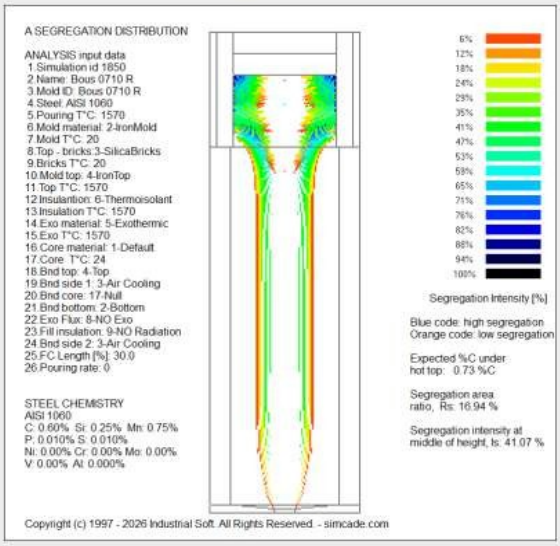


Ingot body : 5950 kg (628 x 629 x 2600mm)
Hot top : 591 kg (933 x 862 x 441mm)

Axial Porosity



A Segregation distribution



Ingot: Bous 0710 R Weight: 6100.0kg H/D: 3.4 Sides: 50

AISI 1060: 0.6C 0.25Si 0.75Mn 0.01P 0.01S

Contact supplier: www.gmh-gruppe.de

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AISI 1075

AISI 1075 is a high-carbon (Carbon: 0.70%-0.80%) known for its excellent balance of hardness, toughness, and durability. It is widely used for knife blades, machetes, and springs due to its toughness and ease of heat treatment. It is commonly available in sheets, strips, and bars.

Composition:

Carbon: 0.70-0.80% , Manganese: 0.40-0.70%

Mechanical Properties:

High tensile strength, good toughness, and excellent fatigue resistance, but low corrosion resistance (must be protected from rust).

Common Applications:

Springs: Leaf springs, flat springs, and washer-type springs.

Blades: Large knives, machetes, and swords due to its ability to take a high-quality edge while maintaining flexibility.

Industrial: Blades for cutting tools, machine parts, and Agricultural equipment

Equivalents:

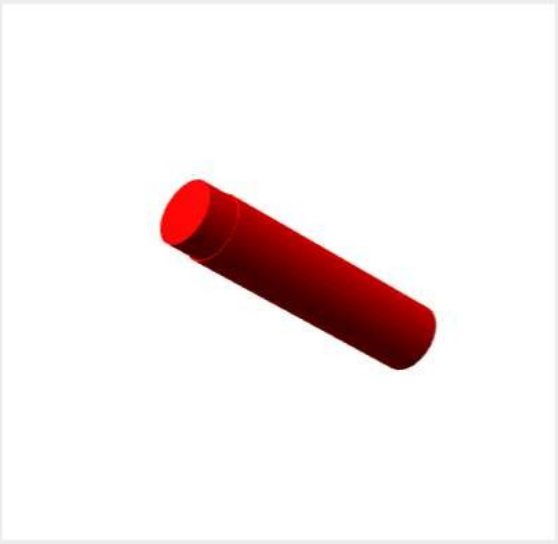
C76D 1.0614 75

5800.0 kg (12760.0 lb) - Bous 58 VK - AISI 1075

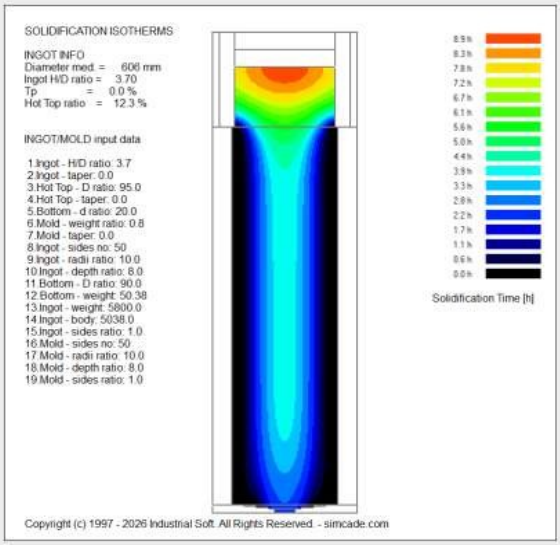
Solidification Analysis
Bous 58 VK (5800.0kg 12789.0lb) / AISI 1075

Equivalent to:
1.0614 75 C76D

Ingot Bous 58 VK

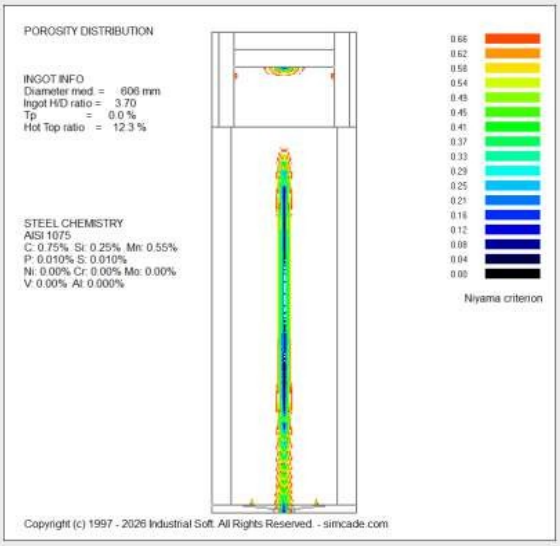


Solidification Isotherms

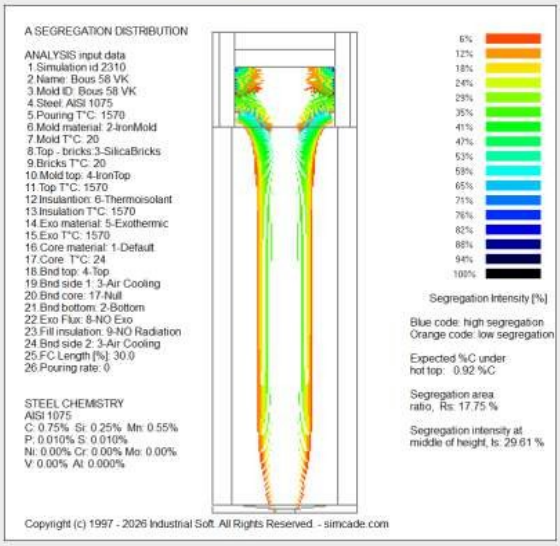


Ingot body : 5655 kg (607 x 608 x 2636mm)
Hot top : 438 kg (901 x 833 x 351mm)

Axial Porosity



A Segregation distribution



Ingot: Bous 58 VK Weight: 5800.0kg H/D: 3.7 Sides: 50

AISI 1075: 0.75C 0.25Si 0.55Mn 0.01P 0.01S

Contact supplier: www.gmh-gruppe.de

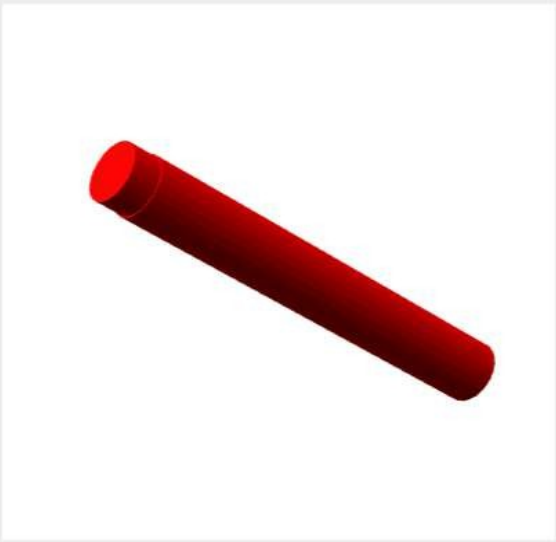
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7810.0 kg (17182.0 lb) - Bous 0600 Z - AISI 1075

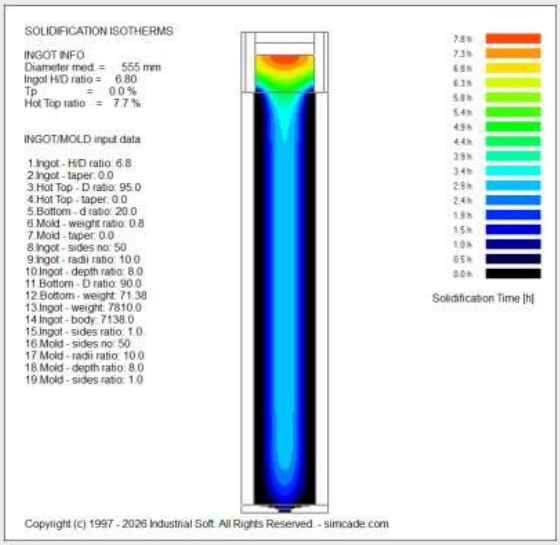
Solidification Analysis
Bous 0600 Z (7810.0kg 17221.0lb) / AISI 1075

Equivalent to:
1.0614 75 C76D

Ingot Bous 0600 Z

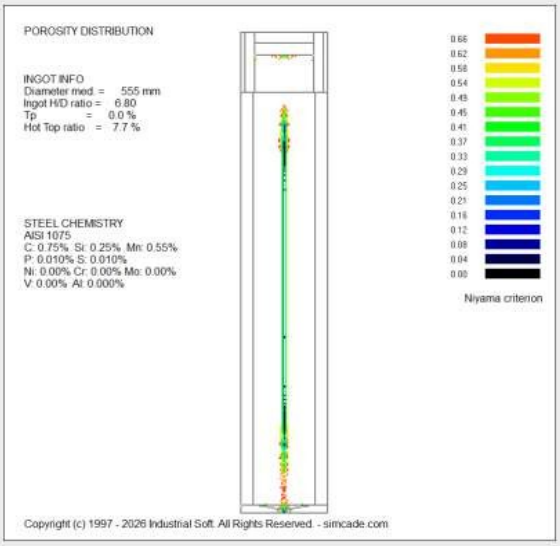


Solidification Isotherms

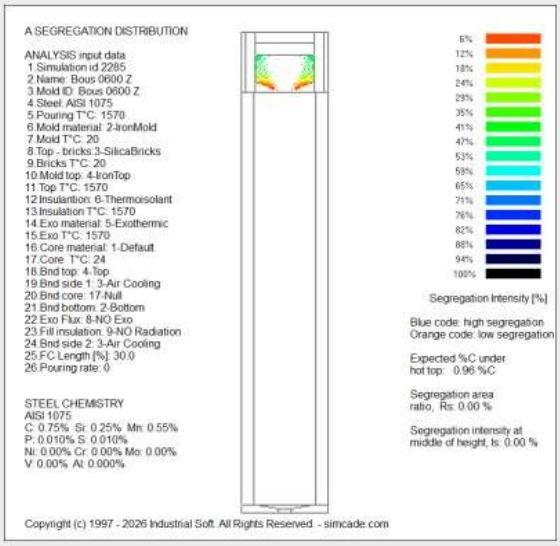


Ingot body : 7604 kg (556 x 557 x 4203mm)
Hot top : 326 kg (827 x 763 x 311mm)

Axial Porosity



A Segregation distribution



Ingot: Bous 0600 Z Weight: 7810.0kg H/D: 6.8 Sides: 50

AISI 1075: 0.75C 0.25Si 0.55Mn 0.01P 0.01S

Contact supplier: www.gmh-gruppe.de

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