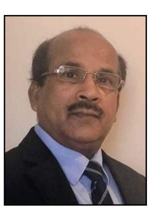
An Automated Quantitative Assessment of Slab Centerline Segregation Using Image Analysis

Digital technologies are transforming industry at all levels. Steel has the opportunity to lead all heavy industries as an early adopter of specific digital technologies to improve our sustainability and competitiveness. This column is part of AIST's strategy to become the epicenter for steel's digital transformation, by providing a variety of platforms to showcase and disseminate Industry 4.0 knowledge specific for steel manufacturing, from big-picture concepts to specific processes.



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Oil and gas pipeline companies are seeking stricter internal quality control for steel pipelines transporting oil and natural gas due to a recent spur in pipeline leaks and accidents and loss of human lives. Line pipe material properties are increasingly under more scrutiny. Not only line pipe, but steels for drilling tubes, collecting lines, crude pressure vessels or storage containers are also subjected to enhanced quality assurance measures for the same safety concerns. While there are quality assurance indicators specified by steel specifications dictated by standardization bodies, pipe and tube manufacturers are additionally incorporating more quality checks in the material specifications. Currently, steels for energy sectors have to guarantee internal cleanliness through quantitative indicators for centerline segregation, inclusion composition and distribution, soundness, inclusion treatment and shape modification, control of dissolved gases, etc.

Of these, centerline segregation is perhaps the most important internal quality consideration. Steels for pipeline applications demand near-free centerline segregation for toughness, soundness and, more importantly, ease of girth welding on-site. There has been concern for center splitting of line pipes during on-site girth welding for centerline segregation in steels, which takes a significant toll on the production process and the project timeline notwithstanding pipeline safety.[1]

Segregation in steel slabs is examined by sectioning a full-width, full-thickness slab sample immediately after solidification. Cross-sectional cast surface along the transverse to casting direction and/or longitudinal to casting direction is machined and macroetched in specific solutions to reveal full cast structure and segregation. The procedure for macroetching is outlined in ASTM E381.[2] The centerline chemical segregation is then compared with a classification rating system indicated by Mannesmann[3] and is universally accepted as a benchmark. Mannesmann's classification system for segregation is based on a qualitative perspective of segregation intensity and distribution along the centerline of cast slab cross-section and the classification has four ratings, as shown in Fig. 1.

However, the classification is entirely based on a visual comparison and therefore is inherently subjective. Today, all pipe manufacturers require a centerline segregation rating of 2 or better as per above qualification rating for acceptable quality criteria of steel for downstream processing. Ironically, most steelmakers falter in assigning a distinct rating when it comes to a segregation pattern resembling an upper side of 2 or lower 3. The indecision is further aggravated by poor light, low-resolution macrographs, obscure etching and poor eyesight. Pipeline operators thus confront a material that may be poor in centerline segregation but was certified to be a better quality rating.

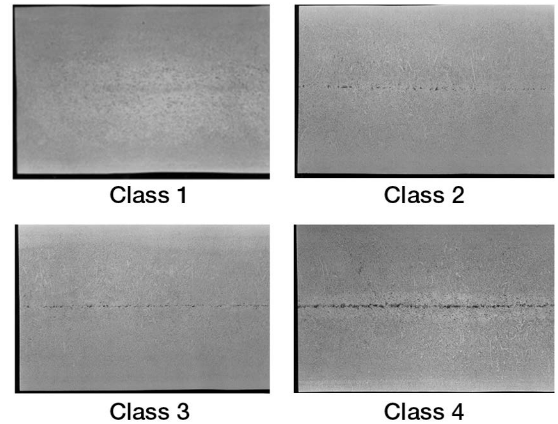
Several global researchers are therefore engaged in finding a universally acceptable centerline segregation rating system that is less subjective[4,5] and offers quantification of segregation density, spread, etc. Spectra Energy Inc. has evolved a quantitative centerline segregation evaluation method[6] that uses circular grids of different sizes, e.g., 1 mm, 3 mm and 5 mm for measurement of segregation spots and outlines a criteria for classification

Table 1

Spectra Classification

Rating	Criteria	Acceptance
Class 1	1 mm < dots ≤3 mm	≤10
	and dots > 3 mm	None
Class 2	1 mm < dots <5 mm	18 max
	and 3 mm < dots <5 mm	5 max
Class 3	Dot ≥5 mm	≥1
	or dots of all sizes	≥19
	or 3 mm ≤dots ≤5 mm	≥6
Class 4	Continuous dots	
	Size of dots	>1 mm
	and length	>10 mm

Figure 1



Mannesmann steel slab centerline segregation classification.

based on population within any 100-mm length along the centerline of full slab width. The logic is cited in Table 1.[6]

Though this classification system attempts to lay out a quantitative estimation of centerline segregation and acceptable quality criteria, it lacks clarity with respect to assigning absolute severity of segregation within an area itself and also avoids addressing centerline shrinkage cavities.

Mannesmann classification still remains the most widely used steel internal quality acceptance criteria for pipemakers despite the subjectivity.

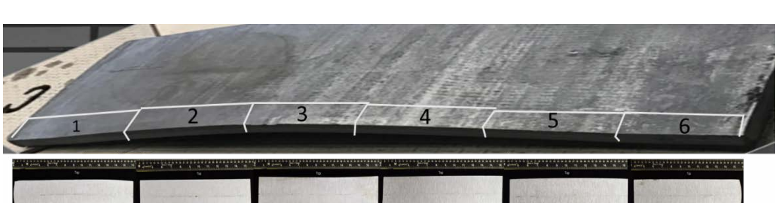
It is envisaged that subjectivity in Mannesmann segregation classification can be minimized if a geometric quantification of the total segregation depicted in each classification system is worked out through an image analysis system, thereby a better tool is available to steelmakers.

Big River Steel is engaged in the production of hot-rolled skelp for line pipe and oil country tubular goods (OCTG) that require sound and clean internal macrostructure. Based on customers' directives requiring slab centerline quality evaluation, an image processing tool was developed to map and quantify segregation spots along the center of slabs and across the full width of slabs. An attempt was made to develop a user-friendly image processing tool that can precisely quantify and calculate dimensional attributes of segregation spots. The analysis was applied to Mannesmann classification macrographs to evolve a benchmarking system that can be applied to any macrographs for comparison and classification and thus can aid in the development of a readily agreeable industry standard for determining severity of chemical segregation.

Experimental

Slab Macroetching — At Big River Steel, slabs are continuously cast through a vertical casting machine with liquid core reduction technology and then directly enter the tunnel furnace. For examination of solidification structure and internal quality of steels, the full-width slab sample is cropped at the exit of the tunnel furnace and taken to the machine shop after cooling for preparation for macroetching. For ease of handling during etching, the full-width slabs are cut into smaller sections 12 inches in length and the cast surface is etched using 50:50 hot hydrochloric acid solution as per ASTM E381-17 specification.[2] Currently, the macroetching is done with an electrolytic etching system. The macroetched surface is photographed at high resolution with a metric ruler placed on top of the slabs for spatial calibration. Use of rotatable cross-polarizers is highly recommended to minimize the effect of specular reflections on the field of view of the image. A typical

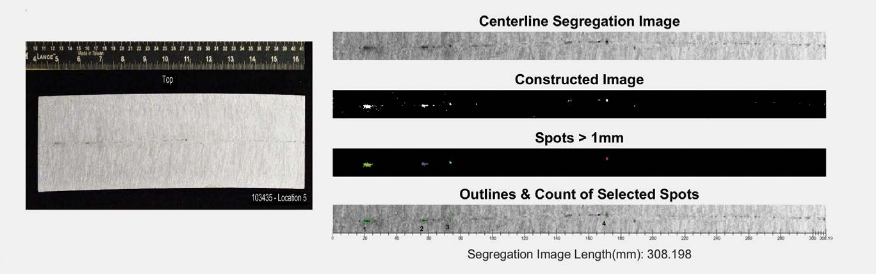
Figure 2



Typical macrograph of an API X70 grade line pipe steel slab.

Table 2

Image Analysis, Output After Extraction and Dimensionality Calculation of the Centerline Segregation Dots

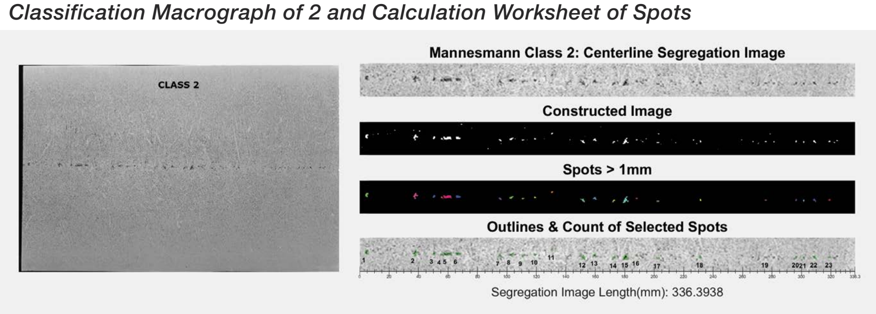


Worksheet			
Dot	Location on slab (mm)	Diameter (mm)	Actual pixel area
1	21.8	3.5	29.8
2	57.5	2.6	16.9
3	73.7	1.3	3.9
4	171.5	1.5	5.2

		Density and size distribution			
Segment (100 mm)	Segregation pixel area	1 mm < dots ≤ 3 mm	3 mm < dots < 5 mm	dots ≥5 mm	Class (as per Spectra rating)
1	50.6	2	1	0	2
2	5.2	1	0	0	1
3	0	0	0	0	1
4	0	0	0	0	1

Table 3

Imaging Analysis of Segregation Spots Indicated in Mannesmann Segregation Classification Macrograph of 2 and Calculation Worksheet of Spots



		Density and size distribution			
Segment (100 mm)	Segregation pixel area	1 mm < dots ≤ 3 mm	3 mm < dots < 5 mm	dots ≥5 mm	Class (as per Spectra rating)
1	76.9	6	1	0	2
2	62.9	9	0	0	1
3	13.3	4	0	0	1
4	12.2	3	0	0	1

slab macrograph is shown in Fig. 2.

Development of the Image Processing Tool

Image Input and Calibration: The macro image is imported into the software application dashboard for analysis. Since the input image can be of different compression types (PNG, TIFF, etc.) and dimensions, it is rescaled and sampled to establish a standard spatial resolution so as to retain the details of its original field of view. The image is spatially calibrated by mapping the pixels of the image per unit length using the reference scale in the image. By this process, the true dimensions (diameter, area, etc.) of the segregation spots, location coordinates, etc., were determined.

Image Editing and Segregation Characterization: After dimensional calibration, the macrograph is subjected to various pre-processing operations such as sharpening, filtering and enhancement to minimize noise. The image is then normalized with respect to pixel intensities for a uniform distribution across the macrograph. The centerline segregation area of the macrograph is then cropped to apply the thresholding algorithm to extract the dark pixels that best represent the chemical segregation (Table 2). After thresholding, the segregation spots are overlaid onto the original image to replicate or mirror the best match. Once the best match is obtained, the properties such as size, pixels, centroid, etc., of each of these dots in the segregation are measured. In the processing, segregation dots are assumed continuous if they are separated by less than 1 mm. The boundaries are drawn around each extracted dot and labeled for identification. Finally, each segregation spot was represented in terms of coordinates, size, pixel area and density per unit length within the slab centerline. The software also enables determination of distribution of inclusions based on size and density per specific length, which is the essence of Spectra rating system.[6] The tool thus allows representation of the segregation spots in any user-defined format. A typical calculation worksheet is shown in Table 2.

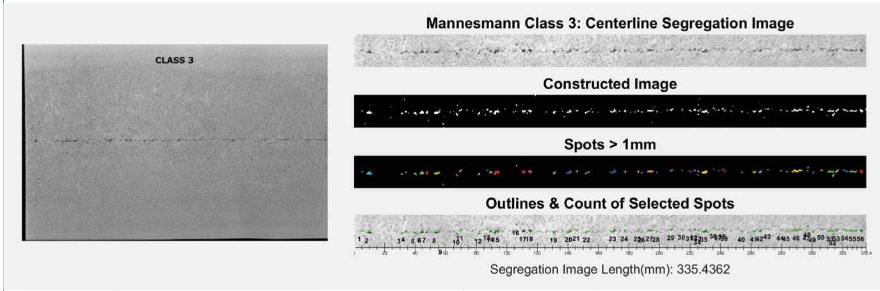
Results and Discussion

Application to Mannesmann Classification Micrographs — The image analysis exercise was then applied to the Mannesmann glossary of macrographs to attempt a quantification of the segregation pattern represented in each rating class. The macrographs of each classification rating were analyzed as illustrated in Table 3. It is worth noting that published macrographs presented in Mannesmann classification ratings do not present any finite dimensions. The slab thickness was found to be 200 mm through communications.[7] The images, therefore, could be spatially calibrated and the segregation spots could be pixelized for quantification as explained earlier. Table 3 illustrates how the segregation spots in Classification 2 were replicated and dimensions measured for analysis and shows the pixel area of the segregation spots calculated for each 100-mm segment of the centerline and a size distribution of the segregations.

Tables 4 and 5 show the corresponding segregation image analysis for classification ratings 3 and 4 in the Mannesmann system.

Table 4

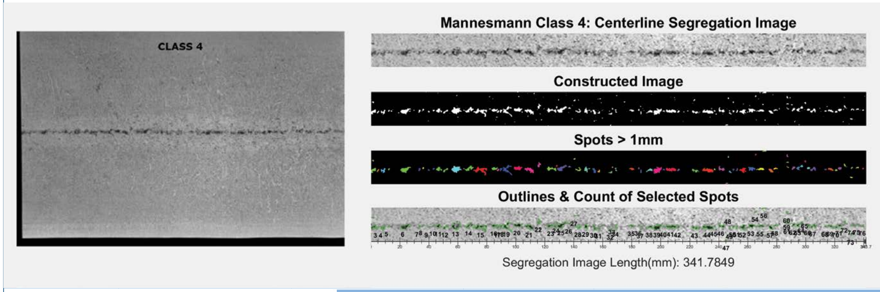
Imaging Analysis of Segregation Spots Indicated in Mannesmann Segregation Classification Macrograph of 3 and Calculation Worksheet of Spots



		Density and size distribution			
Segment (100 mm)	Segregation pixel area	1 mm < dots ≤ 3 mm	3 mm < dots < 5 mm	dots ≥5 mm	Class (as per Spectra rating)
1	116.0	15	0	0	2
2	97.4	13	0	0	2
3	110.6	19	1	0	3
4	70.5	8	0	0	1

Table 5

Imaging Analysis of Segregation Spots Indicated in Mannesmann Segregation Classification Macrograph of 4 and Calculation Worksheet of Spots

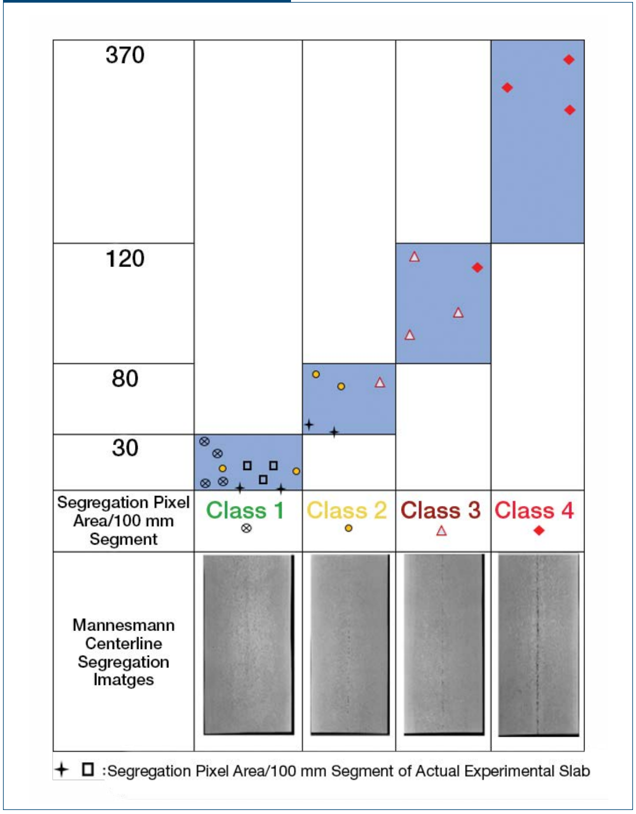


		Density and size distribution			
Segment (100 mm)	Segregation pixel area	1 mm < dots ≤ 3 mm	3 mm < dots < 5 mm	dots ≥5 mm	Class (as per Spectra rating)
1	362.6	12	5	2	4
2	309.7	15	5	0	3
3	285.1	21	4	0	3
4	83.3	12	0	0	2

Classification Based on Segregation Pixel Area

The imaging analysis (Tables 2–5) and the calculated segregation areas per specific centerline segment lengths (100 mm in the current approach) of each classified segregation macrographs thus can be used to provide a quantitative benchmark for classifying

Figure 3



Cumulative segregation pixel area within each reference length (100 mm in this case) evaluated for various Mannesmann classification macrographs. The plot also indicates segregation area per 100-mm length of centerline of slabs of an API X70 slab evaluated using the current image processing tool.

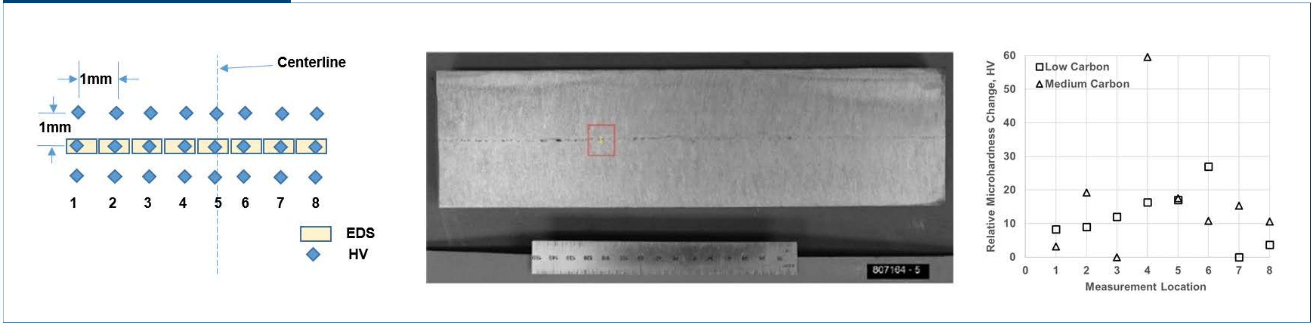
actual macroetched slabs of interest by the steelmakers. Fig. 3 shows the cumulative segregation areas represented by each 100-mm segment length of centerline of slabs in Mannesmann classification and a clear distinction can be outlined between different classes or ratings with progressive increase in pixel areas with marginal overlapping. The minimal overlapping is also due to the natural distribution of segregation to be expected during casting.

Evaluation of Actual Mill Slab Centerline Segregation as per Current Image Processing Tool — The image processing tool was then used to evaluate segregation spot areas of actual mill slabs and compare with the distinction presented in Fig. 3. Each of the macrographs of API X70 slab sections presented in Fig. 2 was analyzed using the tool and the evaluation is shown in the worksheet in Table 2. The resulting segregation pixel areas of all segregation spots per 100-mm length of the current slab are plotted in Fig. 3 for comparison with Mannesmann classification. It is seen that the cumulative pixel area of segregation dots per 100-mm segment length of the macrographs falls within the bands of class 1 and 2 in Fig. 3, indicating a classification of 2 in the quantified Mannesmann scale plot. Additionally, the size and distribution of the segregation dots was also analyzed as per Spectra rating system and was found to be of a rating of 2.

Thus, centerline segregation spots can be analyzed to reveal cumulative pixel area per specific segment length and plotted in Fig. 3 for determination of slab centerline segregation classification. The image processing tool provides a new approach toward objectively classifying steel centerline segregation based on pixel area calculation from the macro images.

Ongoing Work: Pixel Intensity vs. Segregation — Since the analysis tool enables estimation of pixel intensity and size of segregation spots as revealed in the macroetched photographs, the study was further extended to correlate pixel intensity or size with microhardness measurement and chemical segregation measurements of elements Mn, Cr, etc. In this study, the microhardness (Vickers 250 g) is measured across the centerline at regular intervals as shown in Fig. 4 for low-C (0.06 wt.%) and medium-C (0.22 wt.%) steels. The

Figure 4



Microhardness and chemical segregation analysis on spots revealed in macrographs.

polished samples were also scanned across the same spots for elemental analysis in a scanning electron microscope equipped with an energy-dispersive x-ray spectrometer. It was seen that for similar size segregation spot, microhardness readings indicated higher hardness for the medium-C steel slab compared to the low-C steel slab. A comprehensive correlation is worked out for elemental segregation analysis, microhardness and pixel intensity of segregation spots and will be the subject of a future publication.

Conclusions

An image processing tool was developed to quantitatively measure chemical segregation spots in steel slabs. The imaging tool was used to quantify segregation spots in macrographs presented in Mannesmann classification system to evolve a distinctive classification based on image analysis. A normalization approach was developed to apply the imaging analysis to macrographs of all image compression types for uniformity in analysis. The tool can be successfully applied to steel slab macrographs for analysis of segregation and a quantitative classification rating can be obtained. The prospect of the current tool for providing quantitative estimation for all type of natural distribution of segregation spots (shape, size, density, etc.) will enable steelmakers to evolve a more meaningful objective classification system of steel slab centerline segregation analysis.

Acknowledgment

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Did You Know?

AHSS Is a Superb Material for This Car Part

As the vehicles of tomorrow increasingly look to be shared, autonomous and battery-powered, advanced high-strength steels (AHSS) will provide solutions to engineering and design problems. One area they are already having an impact is on battery enclosures, according to George Coates, technical director of WorldAutoSteel.

Speaking during a World Steel Association webinar in May, Coates, who also is the chief technical officer for process consulting firm The Phoenix Group, said battery enclosures need to be intrusion- and crush-resistant, durable, and light.

"We find that the strength and durability requirements quite well lead (automakers) to some of the new AHSS products. The third-generation steels that offer great elongation as well as high strength can be applied very successfully into some of these components."

The webinar, Steel's Role in Future Mobility, was part of the association's ongoing steelTalks series.