Roll Plate vs Roll-Forged Ring
Comparison of Metallurgical Properties[1]

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Abstract:

Large steel towers such as those widely used in power transmission lines are generally supported on a massive concrete base. The base is connected to the steel tower through a monolithic steel base-plate that is bolted to the concrete and welded to the steel tower. Base-plates are fabricated by either cutting a ring from hot rolled plate or roll-forging a ring directly from a forged ingot, also referred to as hot-rolled rings. This paper discusses research conducted to establish whether the two fabrication processes produce equivalent base-plates since differences in microstructural orientation and physical properties may result from the different hot forming processes. A roll-forged ring and hot-rolled plate of near identical metal chemistry and of identical final thickness were tested. Both were heat treated per normal specification for use as a base-plate. Tensile testing and low temperature Charpy-V notch impact tests were conducted in multiple orientations relative to the hot forming direction(s). Microstructures were examined in various related orientations to assess and compare overall microstructure and the effect of hot forming directionality. Microhardness testing was conducted to characterize near surface conditions. Physical properties in critical directions are near equal. Each fabrication method leaves a surface finish and metallurgical microstructure that provides for equal weldability. The results of this study show that both forms of base-plate manufacturing produce products with essentially equivalent functionality.

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Background

Large steel tower structures such as those widely used in power transmission lines are generally supported on a massive concrete base anchor without the use of guy wires. The base is connected to the steel tower through a monolithic steel base plate that is bolted to the concrete base and welded to the steel tower. The steel base plate ring may typically vary from 2 ½" to 6" or more in thickness. Base plate rings are manufactured by two methods. The two methods of manufacture involve somewhat similar hot-forming processes yielding different shapes. In the case of what is commonly called a roll-forged or hot-rolled ring, the furnished shape from the manufacturer is the ring in final dimension, and in the case of what is commonly called hot-rolled plate, the furnished shape from the manufacturer is a rectangular plate from which the ring is then cut. A key difference is in the direction of the hot-rolling (pressing) of the heated steel to make the ring or plate. For the ring shape a heated piece of forged ingot of the correct final weight is punched through to form the initial ring and then pressed out using rotational rolling with radial expansion of the annulus. For the rectangular plate shape either a heated forged billet or a continuous cast material is rolled with expansion in the rolling and transverse axes. Chemically the two materials can be made to the same specifications, but the difference in rolling directions might have an effect on microstructure isotropy. Initial investigation of the literature revealed a lack of directly applicable test data to support a reasonable comparison between the relevant physical properties, and specifically isotropy of physical properties. This study was commissioned to develop the necessary data.

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[1] Authors are employees of GT Engineering a forensic engineering company providing services in metallurgy/materials science, chemistry and mechanical engineering.

[2] Research for this paper was conducted with funding provided by The Steel Structures Division of Thomas & Betts Corporation, Memphis, TN

The starting point for our investigation was acquiring materials supplied under standard ordering procedures for base plates formed by the two processes, both plates being of the same final thickness. The second criteria was to seek as close a metal chemistry match as possible within available roll-forged rings and plate inventory in hand or at the usual supplier. As described in subsequent sections the two 3 ½" thick samples had a very close metal chemistry; they were produced to an identical metal chemistry specification although referred to two different ASTM specifications. The heat treatment was as-provided for each of these specifications, for normal production product used in the manufacture of base plates.

Previous investigation by GT Engineering, including finite element analysis of tower to base plate welds, noted that the critical area of the base plate in resisting loads through the welded joint and in terms of crack initiation and growth is at the top 1" of the plate. Thus, we chose to emphasize acquisition of Charpy V-notch data from the upper 1" of the plate samples. Tensile test data was taken both within the upper 1" and mid-thickness of each plate. Figure 1, after ASTM E23, shows orientations for the test samples along with nomenclature we used to describe directionality. As described later, metallurgical microstructures were examined in all planes relative to the rolling direction at both upper and mid-thickness sample locations. In addition the roll-forged ring microstructures were examined at inner, mid and outer radius locations of the ring.

Literature Review

The mechanical performance of steel is directly related to its microstructure which in turn is controlled by the processing techniques and parameters used to manufacture the material. Three basic processes affect the quality of hot formed steel products: 1) The method of steel production which determines the chemical composition and purity and hence inclusion type and content. 2) The casting method (ingot vs. continuous) which influences distribution of internal flaws and inclusion arrangement in material to be hot worked. 3) The hot working processes parameters and final heat treatment which influence product continuity, microstructure homogeneity and property anisotropy. For steels of similar chemistry and heat treatment, some mechanical properties (toughness, ductility and fatigue) are very sensitive to the inclusion type, content, geometry and spatial distribution. The type and content of inclusions is mainly determined by the chemical composition and deoxidation method. The shape, size and distribution of inclusions depend on the initial as cast structure (coarse dendrite solidification) which determines the starting inclusion distribution and the elongation of the inclusions during subsequent plastic deformation. Improvement in steel cleanliness and processing over the years has resulted in a significant decrease in the harmful impact of inclusions and a decrease in the anisotropy of hot formed steel products.

Ductile fracture in most metals occurs by the nucleation, growth and coalescence of voids, often referred to as microvoid coalescence (MVC). In steels, MVC usually occurs at non-metallic inclusions, hence the size, shape and distribution of inclusion directly influences the ductile fracture process and is reflected in related properties such as total elongation to failure, reduction of area and toughness (impact energy). Yield strength and tensile strength are not influenced as strongly, since MVC occurs after these properties have been determined in a tensile test. Anisotropic properties are a result of the inclusion morphology that develops during the hot deformation processing. Oxide inclusions are relatively brittle and are broken up during reductions. Sulphide inclusions, typically MnS, are plastic under forming conditions and will elongate and flatten significantly during hot deformation. Inclusion morphology has been classified by the definition of the shape factor which is defined as the square of the inclusion perimeter divided by four times the inclusion area. The shape factor increases as inclusion elongation increases. It has been shown that the shape factor increases with amount of hot work up to a reduction ratio of 7:1. At considerably higher reduction ratios, the shape factor decreases due to the breakup of highly elongated inclusions in to smaller pieces. The anisotropy in ductility and toughness increases as the shape factor increases, due to the alignment of the elongated inclusions in the metal flow direction, for example in the rolling direction. The spacing of the inclusions in the failure plane has a strong effect during the growth phase of MVC, since the eventual failure is due to the connection of neighboring voids. Hence specimen orientations that have closer spacing of inclusions in the fracture plane will have lower ductility and toughness since not as much plastic deformation is required to grow the voids to the point where they connect.

The alignment of inclusions can usually be seen in rolled products by viewing the microstructure in different orientations with respect to the rolling direction, often termed longitudinal, transverse and short transverse directions. The differences in ductility and toughness (anisotropy) can be measured by testing samples machined in different orientations relative to the rolling direction. A tensile test in the short transverse direction is also known as a Through Thickness Tensile Test (T^4) and has been shown to be a valid test for lamellar-tearing resistance of welded steel plate.

A review of the literature has shown that inclusion morphology is a key parameter that influences the degree of anisotropy in hot formed steel products. Anisotropy increases with increasing amounts of inclusions and increasing shape factors. When comparing hot forming processes and their relative degrees of anisotropy for a given steel, the key factor is how the plastic deformation affects the inclusion morphology. The influence of inclusion morphology is reflected in changes in the ductility and toughness of specimens in different orientations within the formed part. Key parameters in hot-rolling and roll-forging that influence inclusion morphology include the reduction ratio and amount of reduction per pass. Roll-forging is more complex than traditional hot rolling since rolling reduction is occurring in two directions simultaneously. Studies on inclusion shape have shown that bar shaped inclusions are less detrimental to ductility and toughness then plate shaped inclusions. Under some conditions, the three dimensional deformations taking place during ring forming would be expected to produce fewer plate shaped inclusions than traditional hot-rolling.

Weldability as defined by ASM International: “The capacity of a material to be welded under the imposed fabrication conditions into a specific suitably designed structure and to perform satisfactorily in the intended service". For steels, the composition (related to hardenability), the thickness of the material and the susceptibility to lamellar tearing strongly influence the weldability. The susceptibility to lamellar tearing is related to the inclusion content and distribution in hot worked steel. Due to the cleanliness of modern steels, lamellar tearing is usually not of concern. Weldability decreases as hardenability and thickness increase because they promote the formation of microstructures that are more sensitive to cracking in the heat affected zone. The hardenability of steel depends on its chemical composition. The equivalent carbon content or Carbon Equivalent (CE) has been developed to assist in evaluating the weldability of hardenable steels based on chemical composition. A common formula to determine the CE of steel is shown below:

$$CE = \%C + \frac{(\%Mn + \%Si)}{6} + \frac{(\%Cr + \%Mo + \%V)}{5} + \frac{(\%Cu + \%\,Ni)}{15}$$

Lower CE's generally increases the weldability of steel. Steels with CE's greater than 0.35 generally require preheating and or post heating to avoid cracking. The weldability of steels with similar compositions, microstructures and properties should be the same. Weldability may also be affected by surface condition, contamination or irregularity. Hot rolling and roll-forging both involve final surfaces formed by contact with smooth rollers under similar atmospheric conditions. Roll-forged rings do have a very slight radial curvature which would have no effect on a circumferential plate to tower weld.

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Materials

It was not feasible to obtain two samples with the same overall reduction ratio due to the differences between the forming techniques. It was therefore determined to assess the properties of commercially available roll-forged ring and hot-rolled plate material of the same thickness. The analysis therefore compares the two available products rather than only the difference between the two manufacturing methods. To minimize the effect of compositional variation, representative samples of hot-rolled plate and a roll-forged ring with similar chemical compositions were selected. The chemical compositions of the two materials used in this study are shown in Table 1, along with the chemical requirements of ASTM A588 Grade B for reference purposes. The roll-forged ring was specified as A588 Grade B material, while the hot-rolled plate was specified as ASTM A871 Grade 60 Type II material. The two material specifications have the exact same chemical requirements and both are specified as having atmospheric corrosion resistance index of 6.0 or higher, as calculated per Guide G101-Predictive Method Based on the Data of Larabee and Coburn. The similarity in composition of the two products should lead to no differences in weldability. The only difference between the two standards is the inclusion of a Charpy V-Notch requirement and specification of optional heat treatments in ASTM A871.

Table 1: Chemical Compositions

Element/Alloy	ASTM A588	Roll-Forged Ring	Hot-Rolled Plate
C	0.19 max	0.14	0.17
Mn	0.75-1.25	1.13	1.14
P	0.04 max	0.007	0.011
S	0.05 max	0.012	0.007
Si	0.15-0.50	0.32	0.341
Ni	0.50 max	0.17	0.16
Cr	0.40-0.70	0.42	0.48
Mo	….	0.03	0.008
Cu	0.20-0.40	0.39	0.262
V	0.01-0.10	0.065	0.051
Nb	…	0.003	0.002

Of particular interest in the materials selection were the non-metallic inclusion-forming elements such as Sulfur, Silicon, and Manganese. While metallic elements will have greater effect on the strength, these effects will be generally isotropic. The geometry and dispersion of the non-metallic inclusions may have a strong effect on the directionality of the material properties. Though the melting and refining processes utilized in production of the steel will affect the number and size of the inclusions, samples with identical production processes other than hot-rolling versus roll-forging were not available.

Both the hot-rolled plate and roll-forged ring were subject to post-forming heat treatment. The hot-rolled plate was austenitized at 1670^{o}F for 152 minutes, then tempered at 1200^{o}F for 176 minutes; no quenching information was available. The roll-forged ring was austenitized at 1600^{o}F for 120 minutes, quenched in agitated water at 80^{o}F, then tempered at 1100^{o}F for 300 minutes and cooled in still-air.

Microstructure

The microstructures of the two sample materials were examined to characterize the isotropic degree of the grain structure as well as the size, shape, and distribution of the inclusions. The hot rolled plate sample microstructure was examined at the top surface and mid-thickness locations to determine the homogeneity of the microstructure through the plate thickness; microstructures were evaluated on planes parallel to rolling directions (longitudinal and short transverse). Figure 2a shows the etched microstructure of the plate intersecting the top surface in the longitudinal plane. It is apparent in this image that there is a thick layer of a tempered transformation product, over 20 mils thick, at the top surface. Figure 2b shows the etched microstructure of the plate near the top surface in the longitudinal plane. The microstructure shows equiaxed grains, course banding, and a small number of spheroidized inclusions. Figure 2c shows the etched microstructure of the plate mid-thickness in the longitudinal plane. The microstructure shows equiaxed grains, course banding, and numerous spheroidized inclusions.

The microstructure of the roll-forged ring specimen was examined at the top surface at the inner edge of the ring, the center of the ring, and the outer edge of the ring to determine the homogeneity of the microstructure radially through the ring; no significant variation was identified between the inner diameter and outer diameter surfaces. Microstructures were examined in circumferential and axial planes. The microstructure in the center, mid-thickness of the ring was also examined to determine the homogeneity through the ring thickness. Figure 3a shows the etched microstructure of the roll-forged ring intersecting the top surface in the circumferential plane. Equiaxed grains and slightly elongated inclusions are apparent in this microstructure; no martensite layer is apparent at the top surface. Figure 3b shows the etched microstructure of the roll-forged ring near the top surface in the circumferential plane. The microstructure shows equiaxed grains and elongated inclusions. Figure 3c shows the etched microstructure of the roll-forged ring mid-thickness in the circumferential plane. The microstructure shows equiaxed grains, fine banding, and elongated inclusions.

Comparison of the hot-rolled plate and roll-forged ring microstructures revealed several similarities and differences. Both materials had equiaxed grains of approximately the same size; this is likely the result of similarities in their chemical compositions and heat treatments. The hot-rolled plate has a thick layer of tempered transformation product at the top surface which is not present on the roll-forged ring. The hot-rolled plate shows coarse banding both near the top surface and at the mid-thickness locations while the roll-forged ring shows fine banding at the mid-thickness location and no banding near the surface. The hot-rolled plate evidenced higher concentrations of non-metallic inclusions than the roll-forged ring; however the inclusions in the hot-rolled plate were spheroidized while the inclusions in the roll-forged ring were elongated in the circumferential direction. This variation is most likely caused by differences in forming processes, particularly the reduction ratio during rolling, and will have an influence on the material toughness in the rolling/circumferential direction. No microstructural differences were found that would suggest any difference in the weldability of the two products.

Hardness

Table 2: Hardness Measurements			
Roll-Forged Ring		Hot-Rolled Plate	
Distance From Top Surface (mils)	Rockwell B Hardness (HRB)	Distance From Top Surface (mils)	Rockwell B Hardness (HRB)
5.7	86	2.5	89
25.0	89	10.5	96
78.0	91	67.0	95
150.6	90	131.8	98
221.6	87	200.3	98
293.9	92	249.4	96
354.1	89	306.8	94
416.3	89	371.7	93
446.7	91	444.7	93
458.0	85	528.8	92

Table 2 shows comparative microhardness measurements near the upper surfaces of the hot-rolled plate and the roll-forged ring. Consistent with the similarities in metal chemistry, heat treatment and microstructures both materials showed similar hardness levels, with the hot-rolled plate material consistently slightly harder than the roll-forging. Neither material exhibited any remaining martensitic transformation product at or near the surface which is confirmed by the microhardness values.

Tensile Properties

The tensile properties of the hot-rolled plate material were tested parallel to the rolling direction at the top surface and mid-thickness, perpendicular to the rolling direction at the top surface and mid-thickness, and in the through-thickness orientation. Results from the tensile testing, taken as the average of 3 tests, are shown in Table 3. The variation between the properties tested parallel and perpendicular to the rolling direction were generally small, though greater in the mid-thickness material and in the yield strength; the largest observed variations were in the yield and tensile strengths in the mid-thickness material, 1.22% and 0.59% respectively . The greatest variation in elongation with orientation was 11.46% in the mid-thickness material. There was substantially greater variation in the yield and tensile strengths between the top surface and mid-thickness materials than between orientations: 16 to 17% in yield strength, 8% in tensile strength. The variation in elongation between the top surface and mid-thickness materials was significantly greater in the rolling direction than perpendicular to the rolling direction, 15.66% versus 2.30%. The through-thickness properties were generally the same as the mid-thickness properties measured perpendicular to the rolling direction.

Table 3: Rolled Plate Material Tensile Properties			
Sample	Yield Strength (ksi)	Tensile Strength (ksi)	Elongation in 4D Gage Length (%)
Through-Thickness	62.93	85.00	28.67
Rolling Direction Top Surface	75.17	92.83	27.67
Rolling Direction Mid-Thickness	62.83	84.9	32.00
Perpendicular to Rolling Direction Top Surface	75.20	93.00	29
Perpendicular to Rolling Direction Mid-Thickness	62.07	85.40	28.33
Top Surface Parallel-Perpendicular Variation (%)	0.04	0.18	4.82
Mid-Thickness Parallel-Perpendicular Variation (%)	1.22	0.59	11.46
Rolling Direction Top Surface-Mid-Thickness Variation (%)	16.41	8.55	15.66
Perpendicular to Rolling Direction Top Surface-Mid-Thickness Variation (%)	17.64	8.17	2.30

The tensile properties of the roll-forged ring were tested parallel to the ring circumference at the top surface and mid-thickness, parallel to the ring radius at the top surface and mid-thickness, and in the through-thickness orientation. Results from the tensile testing, taken as the average of 3 tests, are shown in Table 4. Variations between the circumferential and radial directions in yield and tensile strengths were generally greater in the top surface material and in the yield strength; the largest variation was in the top surface material yield strength, 12.24%. The greatest variation in elongation with orientation was 18.81% in the mid-thickness material. Variations in yield and tensile strengths were somewhat greater between the top surface and mid-thickness materials than between orientations: 14.95% and 9.35% respectively in yield strength, 5.83% and 7.24% respectively in tensile strength. Variation in elongation between the top surface and mid-thickness materials was only slightly greater in the circumferential direction than in the radial direction, 8.60% versus 6.82%. The through-thickness properties were generally the same as the mid-thickness properties in both orientations, though the elongation was somewhat less but still within specifications.

Table 4: Roll-Forged Ring Material Tensile Properties			
Sample	Yield Strength (ksi)	Tensile Strength (ksi)	Elongation in 4D Gage Length (%)
Through-Thickness	55.97	82.90	24.33
Circumferential Direction Top Surface	66.20	86.40	31.00
Circumferential Direction Mid-Thickness	56.3	81.37	33.67
Radial Direction Top Surface	58.10	89.73	29.33
Radial Direction Mid-Thickness	52.67	83.23	27.33
Top Surface Circumferential-Radial Variation (%)	12.24	3.86	5.38
Mid-Thickness Circumferential-Radial Variation (%)	6.45	2.29	18.81
Circumferential Top Surface-Mid-Thickness Variation (%)	14.95	5.83	8.60
Radial Top Surface-Mid-Thickness Variation (%)	9.35	7.24	6.82

Comparing the tensile testing results of the roll-forged ring and hot-rolled plate materials reveals that the strength and ductility of the roll-forged ring are more anisotropic but generally more consistent through the material thickness than in the hot-rolled plate. The single deviation from this pattern is the variation in elongation between the top surface and mid-thickness material oriented perpendicular to the rolling or circumferential direction. Also, while the strength of the hot-rolled plate was higher than that of the roll-forged ring, likely due to variations in the carbon content, the roll-forged ring showed greater or virtually equal ductility in all but the through-thickness orientation.

Toughness

The toughness of the sample materials was estimated by Charpy V-Notch testing. Test samples were all removed from the top surface material, as this is the location where fracture will most likely initiate during use. Testing was performed at 0 ^{o}F and -20 ^{o}F. Results of the testing are shown in Tables 5 and 6; the results are all the average of 3 tests. For labeling purposes, the rolling direction of the plate is considered to be the longitudinal direction, the transverse direction is perpendicular to the rolling direction, and the vertical direction is through-thickness.

Table 5: Charpy V-Notch Tests at 0 ^{o}F			
Hot-Rolled Plate	Ft-Lbs	Roll-Forged Ring	Ft-Lbs
Transverse Specimen Longitudinal Notch	59.5	Radial Specimen Circumferential Notch	38.7
Transverse Specimen Vertical Notch	37.0	Radial Specimen Vertical Notch	39.3
Longitudinal Specimen Transverse Notch	67.5	Circumferential Specimen Radial Notch	80.3
Longitudinal Specimen Vertical Notch	50.0	Circumferential Specimen Vertical Notch	104.3

Table 6: Charpy V-Notch Tests at -20^{o}F			
Hot-Rolled Plate	Ft-Lbs	Roll-Forged Ring	Ft-Lbs
Transverse Specimen Longitudinal Notch	42	Radial Specimen Circumferential Notch	28.7
Transverse Specimen Vertical Notch	28.0	Radial Specimen Vertical Notch	25
Longitudinal Specimen Transverse Notch	61.5	Circumferential Specimen Radial Notch	77.3
Longitudinal Specimen Vertical Notch	42.3	Circumferential Specimen Vertical Notch	86.7

It is apparent from the above data that the roll-forged ring shows greater overall anisotropy than the hot-rolled plate. It is worth noting that the Charpy values of the circumferentially and vertically oriented notches in the roll-forged ring radial specimens are virtually identical, while significant variation is observed between the longitudinal and vertically oriented notches in the hot-rolled plate transverse specimens. This indicates microstructural refinement in two directions in the roll-forged ring, vertical and radial, and only one direction in the hot-rolled plate.

Experience has shown us that when used as tower baseplates, fractures initiate at the top surface in the plane of the tower side and propagate vertically into the baseplate material before eventually curving to propagate radially and circumferentially. The critical direction for fracture initiation and early propagation in a roll-forged ring is therefore vertical in a radially oriented specimen. In a baseplate cut from a hot-rolled plate, the orientation of the plate relative to applied loading will be unknown so the critical direction will be vertical in a transverse specimen. The Charpy V-Notch values for the two materials are virtually identical in this configuration.

Conclusions

Based on the comparisons of mechanical test properties shown above there does not appear to be either a distinct advantage or disadvantage in serviceability when near identical metal chemistry hot-rolled plate is compared to roll-forged ring. The slightly different tensile strengths between the compared materials would be consistent with the additional carbon in the hot-rolled plate. The roll-forged ring has slightly greater anisotropy when comparing directional tensile properties at a specific depth in the part. However, the hot-rolled plate exhibits greater variability in tensile properties when comparing the near upper surface region and the mid-section of the plate. This is likely due to the increased effective reduction with the roll-forged ring.

Impact toughness as determined by Charpy V-notch testing on standard sized samples again provides limited distinction between the two methods of plate fabrication. Assuming a circumferential tower weld with crack initiation at the weld root, the roll-forged plate offers virtually identical performance in through-plate (radially oriented sample with a vertical notch) Charpy toughness to the same construction using a ring cut from a hot-rolled plate (transverse oriented sample with a vertical notch). With a circumferential weld both longitudinal and transverse directions would be pertinent over portions of the weld on a hot-rolled plate ring; the transverse orientation, having the lower toughness, would thus be the design limiting value.

Neither forming process produced deleterious microstructures. There was some expectation that the hot-rolled plate would be prone to plate-like Mn-S inclusions, but the tested sample showed primarily spherical inclusions. There were likely Mn-S stringers in the circumferential plane of the roll-forged material but not of a size or extent to prevent the material from meeting the toughness and ductility requirements of ASTM A871. Microhardness testing from the upper surface proceeding into the material showed that the roll-forged product was slightly softer than the hot-rolled plate, but neither material was particularly hard; all measurements were in the Rockwell B scale range. There was no evidence of a hard surface structure, e.g. such as a martensitic layer, on either of the tested plates, though the hot-rolled plate did have a structure at the top surface that differed from the body of the material.

The surfaces of the samples received by GT Engineering were both clean of scale with a fairly smooth topography. There was a slight amount of radial curvature in the roll-forged material. Similarities in metal chemistry, microstructure, inclusion content and morphology, as well as surface condition indicate that these two products would be equally weldable.

Glossary

Charpy V-Notch: an impact test in which a rectangular specimen with a 'V' shaped notch cut into the midpoint of the length is struck by a pendulum mounted striker. The energy that is absorbed in fracture is calculated by comparing the height to which the striker would have risen had there been no specimen to the height to which it actually rises after fracture of the specimen.

Banded Structure (Banding): A segregated structure consisting of alternating, nearly parallel bands of different composition and possibly microstructure. Banding is typically aligned in the direction of primary flow in hot working but can also be caused by conditions from when the material was cast. Coarse banding indicates relatively wide banding in the structure, while fine banding indicates relatively thin lines made by the banding suggesting greater grain refinement.

Dendrite: A crystal with a treelike branching pattern, most evident in cast metals slowly cooled through the solidification temperature range. The structure can be coarse or fine depending on the relative size of the structure.

Equiaxed Crystals/Grains: Crystals or grains that are the same length in every direction. Equiaxed grains promote isotropic properties in a material.

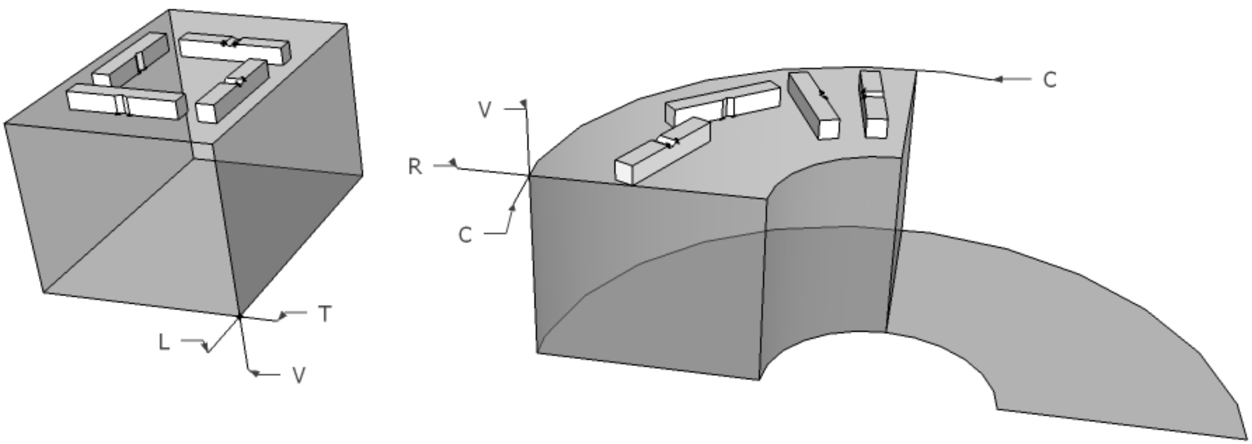
Inclusion Morphology: The shape of the non-metallic particles in the metal matrix. Inclusions are usually compounds such as oxides, sulfides, or silicates but may be composed of any material that is essentially insoluble in the metal matrix.

Isotropy: the properties are the same in all directions. The opposite is anisotropy in which the properties are specific to the direction. Equiaxed grains and low shape-factor inclusion morphologies promote isotropy in materials while elongated grains and high shape-factor inclusion morphologies promote anisotropy.

Reduction Ratio: the ratio of the final dimension following forming to the original dimension of the part prior to forming. Forming can be from rolling, forging or drawing. Roll Reduction refers specifically to the reduction in thickness due to hot rolling. There is a minimum reduction ratio, specific to the forming method, required to remove casting defects from a material to achieve suitable mechanical properties.

Shape Factor: The effect on the properties of the material due to the inclusion morphology. The higher the shape factor the greater the effect of the overall material properties. The shape factor will be lowest when the inclusions are spherical and increase as the inclusions elongate.

Tempered Transition Product: A non-equilibrium crystalline structure formed during rapid cooling of a material that has subsequently been modified by reheating.



Rolled Plate
1a

Roll-Forged Ring
1b

Figure 1 - Geometry of materials and sample orientations.

a) Geometry of hot rolled plate. L designates the longitudinal direction (rolling direction), T and V designate transverse and vertical directions relative to rolling direction
b) Geometry of roll-forged ring. C, R and V designate circumferential, radial and vertical directions

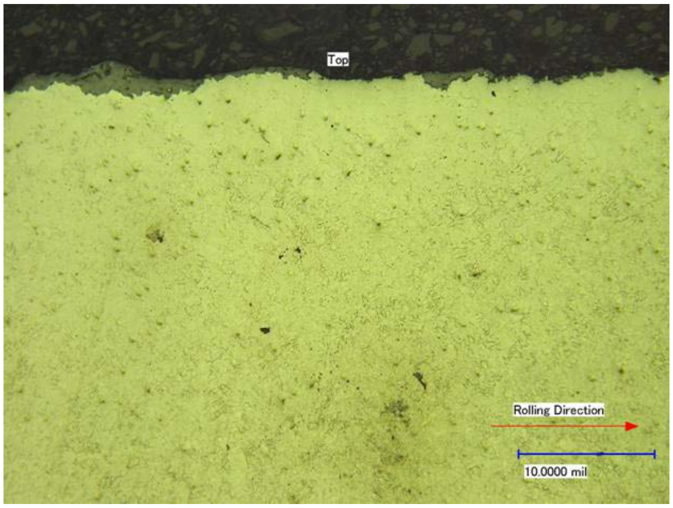


Figure 2a Hot-rolled plate at upper surface of plate

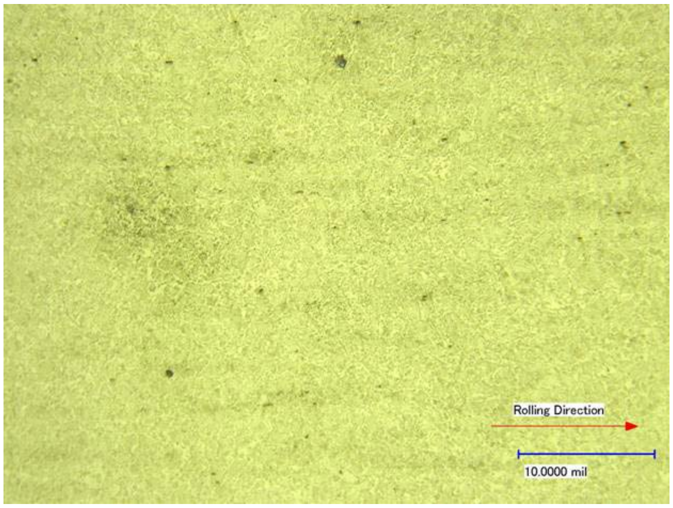


Figure 2b Hot rolled plate at near upper surface

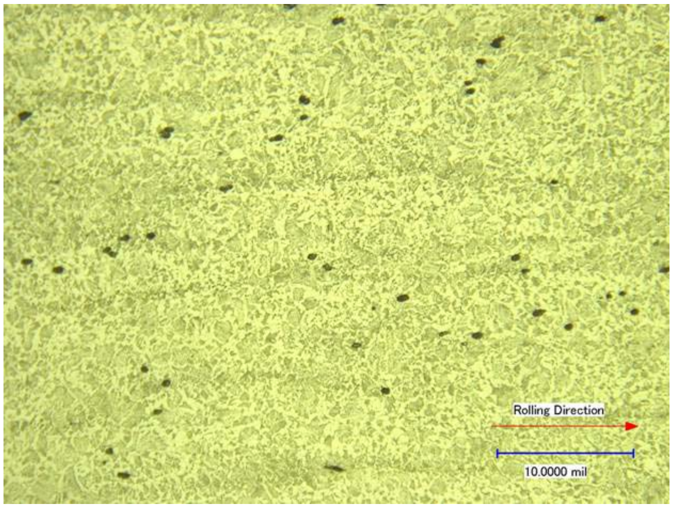


Figure 2c Hot rolled plate at mid-section of thickness

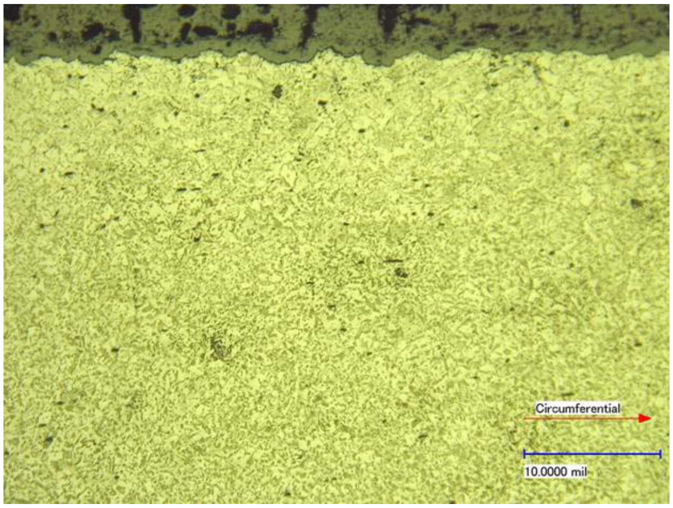


Figure 3a Roll-forged plate at top surface of plate

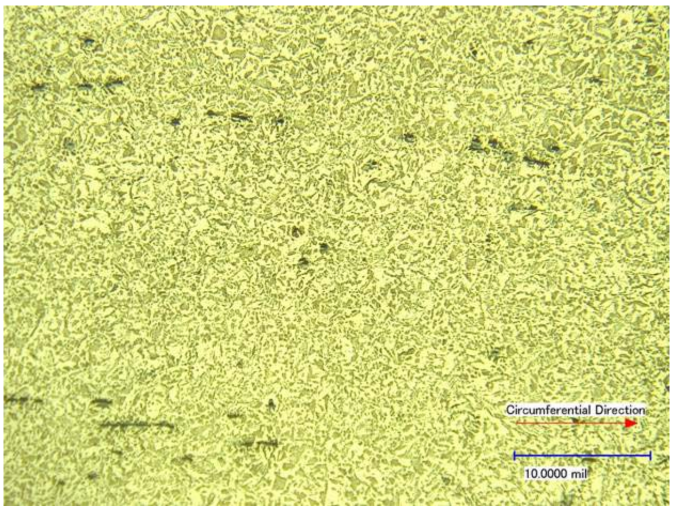


Figure 3b Roll-forged plate near top surface of plate

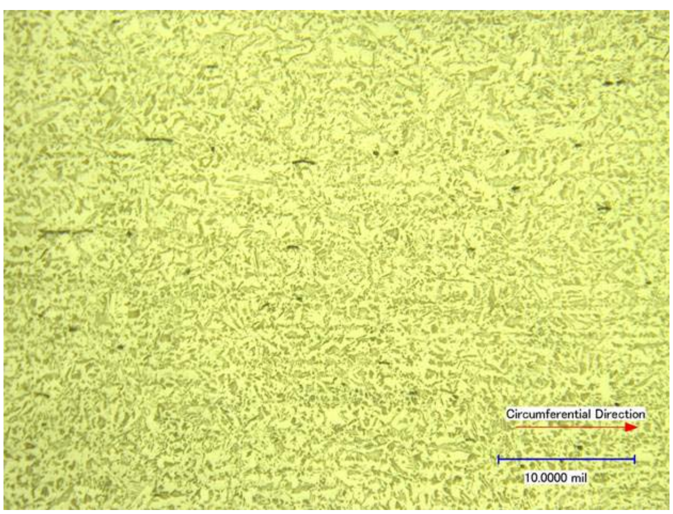


Figure 3c Roll-forged plate at mid-thickness of plate