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A Literature Review of the Effect Hot Reduction Has on the Structure, Mechanical Properties, and Fatigue Performance of Continuous Cast Steel

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A LITERATURE REVIEW OF THE EFFECT HOT REDUCTION HAS ON THE STRUCTURE, MECHANICAL PROPERTIES, AND FATIGUE PERFORMANCE OF CONTINUOUS CAST STEEL

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CHAPTER 1. INTRODUCTION

The traditional process of steel production consisted of melting scrap or pig iron, refining the molten metal, and teeming the liquid steel into large ingot molds. These ingots required extensive high temperature soaking and hot reduction by rolling as the steel is processed into slabs, blooms and billets. These intermediate products go through a series of reheat and rolling operations to produce a finished product such as bars and other shapes (Irving, 1993). As a result, ingots are reduced extensively and often as much as 50, 100, to 200 times the original cross sectional area. Although some ingot casting capacity still exists, continuous casting directly into slabs, bloom, and billets has largely displaced that manufacturing method. In North America ingot casting has declined from 65% of steel production in 1983 to less than 20% today (Irving, 1993). Irving (1993) has detailed the history and evolution of continuous casting technology. The advantages of continuous cast products to the industrial economy include: (1) a lower product cost, (2) substantial energy savings, (3) higher product yields, and (4) increased production efficiency. Another advantage of continuous casting is the practice of linking direct rolling with the casting process. Direct rolling eliminates the need for reheat operations and improves surface quality with lower levels of mill scale. Tipton (1983) outlined other merits for continuous cast steel: (1) improved chemical homogeneity, (2) more isotropic properties than ingot cast, and (3) improved non-metallic inclusion morphology by proper processing. As a result of these benefits, continuous cast steel products are in high demand and will be used in many critical components such as axles, gears, engines, and drive trains (Islam, 1989).

Commercial requirements specifying a minimum area of reduction can severely limit the offerings of a particular steel producer with regard to the range of product sizes they can supply. The problem is created because the as cast section size does not allow the required amount of reduction in the cross sectional area to the final product. Alternately, this fact requires the steel mill to produce a larger number of as cast billet sizes to meet industry specifications than is economical (Morris, Ryalls, and Wade, 1991).

Hawbolt, Weinberg, and Birma-Combe (1979) stated, " The quality of steel produced by continuous casting, as compared to static (ingot) casting, is a function of the defects present in the as cast structure and the changes in the size and distribution of those defects with subsequent hot working." These researchers found that ingot castings tend to exhibit coarse dendritic structures in the center of the product with accompanying macro segregation and centerline porosity. These ingot castings generally are extensively hot worked which provides the force and deformation to close porosity, break up non-metallic inclusions, and reduce segregation.

Morris, Albiston, and Igham (1990) stated the area of reduction currently specified for a continuous cast product represents an empirical measure of the minimum deformation necessary to develop material properties similar to those of the ingot cast product. In many cases this demand for a minimum area of reduction limits the product size range of a particular steel mill because the established billet section does not allow the required reduction of area in the finished product. In absence of fundamental information as a guide, steel mill operators rely on empirically derived procedures, and a traditional minimum reduction ratio such as 6:1 for continuous cast and rolled material. Morris et al. (1990) identified a clear need for a fundamental appraisal of the types of manufacturing processes which can be used to optimize the processing of continuous cast sections to the achieve desired results of structure, properties, and performance with a minimum of mechanical deformation. Adoption of the optimal deformation procedures will allow a wider range of sizes to be obtained from continuous cast sections and thereby offer reduced production costs and greater flexibility in operations.

Brunet (1985) stated the fundamental concern of industry, "If a forged part were to be manufactured from a continuous cast steel containing porosity, and if the forging grain flow were such that a pore surfaced in a critical zone, it is evident that part performance could be adversely affected."

Statement of the Problem

The principle problem is one of identifying the precise degree of hot reduction required to provide continuous cast properties equivalent to ingot cast material. There is concern among industrial users that the small as cast sectional sizes of continuously cast steel products may not receive sufficient hot work or hot reduction to produce structural or mechanical properties characteristic of products produced from cast ingots. Rittgers, Frost, Krause, and Matlock (1989) stated metallurgical structure, chemical composition, internal cleanliness, and process related defects control the properties of continuous cast steel. The properties of greatest interest to the design engineering community include: (1) tensile properties such as yield strength, (2) ductility as represented by percent reduction in area and elongation, (3) impact strength, and (4) fatigue performance.

(McCreery, 1984). The design community is reluctant to utilize steels with low reduction ratios due to the uncertainty about the consistency of the mechanical and structural properties of a component during its service life. The design community's reluctance to utilize continuous cast steel is based on the fact that most past design and product data, upon which engineering decisions are made, was derived from ingot cast material. Again the basic issue is, can a model or methodology be established to predict or determine the required level of hot reduction that continuous cast steel must be subjected to produce a final product that is equivalent to ingot cast steel in mechanical, fatigue and other properties? An alternative would be the development of a set of steel production process controls and the delineation specific process parameter specifications tailored to an individual mill that would guarantee the desired properties. This alternative would also require the development of a verification or validation method for the products of each specific steel mill utilized in customer applications.

Statement of Purpose

The purpose of the investigation is to review the published literature concerning investigations of the effects of hot reduction and other factors have on the structure, properties, and performance of continuously cast steel products. Of principle interest is the recognition of a minimum reduction ratio needed to provide steel with acceptable design options for industrial customers. The minimum reduction or rolling ratio is the cross-sectional area of the cast billet divided by the corresponding area of the final rolled product required to assure the breakdown of the as cast structure, and the attainment of satisfactory mechanical properties. The investigation is also to determine the status of the development of a means of predicting or modeling the effects of various steel production parameters on the characteristic structural and mechanical properties of continuous cast billets. The review will also investigate the methodology researchers are utilizing to analyze this problem. This includes analysis of the design of experimental methods and techniques, population sampling, control, measurement, reliability and verification.

Statement of Need

The concern about reduced mechanical properties and poor fatigue performance has limited the applications for continuous cast steels to smaller section components. In many industries the ratio of reduction from cast and rolled bar to component cross section has traditionally been limited to a ratio range of 4:1 to 8:1 (Rittgers, Frost, Krauss, and Matlock, 1989). For example, a 140 mm continuous cast square billet would have to be reduced to 80 mm in diameter bar for a 4:1 ratio or 65 mm for an 8:1 ratio before industry would determine the material fit for use. It is therefore, of great interest to industry to determine if a relationship exists between the degree of hot reduction and consistency of mechanical and structural properties. Also, there is a need to develop a methodology to validate the reliability of steel produced by continuous casting intended for use in critical design applications when the steel does not meet the traditional specifications for minimum reduction ratio. Fattorini and Grifoni (1990) stated that steel to be supplied to the automotive and machinery industries must posses high reliability to meet the expected quality levels for the products produced. This reliability is closely related to the quality of the original billets and blooms and the procedures used in the casting and rolling processes.

Research Questions

The principle research question to be answered is, "can a model or methodology be developed to determine the amount of hot reduction required to produce consistent mechanical properties and structural integrity in continuous cast steels?" Industry wants to identify the product sizes that can be produced from a particular continuous cast billet section size and utilized in critical applications. The end product section size is determined and limited by the need: (1) to consolidate central looseness and voids, (2) minimize the effects of detrimental non-metallic inclusions, and (3) to develop mechanical properties suitable for the design application (Morris, Ryalls, and Wade, 1991).

This study will also investigation, "what methodologies are utilized by researchers to evaluate and characterize the material examined and the success of these methods as predictors?" These methods might include tensile testing, Charpy impact testing, rotational bending fatigue testing, torsional fatigue testing, gamma ray absorption, ultrasonic examination, macro and micro metallographic techniques (Morris, Ryalls, and Wade, 1991). McCreery (1984) utilized tensile tests, impact tests, and rotating beam fatigue tests. Dyck, Frost, Krauss, and Matlock (1989) used tensile tests, impact tests, and torsional fatigue tests. Stovar and Kolarik (1987) used ultrasonic inspection techniques to characterize non-metallic inclusions in their test samples. And Schauwinhold (1982) included a weldability test.

This investigation will also evaluate the experimental deign and research methods used by researches in this field. These studies will be examined for the following characteristics. Does the research build on already accepted knowledge or does it break new and original path of investigation? Will the researchers be able to use their research to make predictions? What is the reliability and validity of the research done?

Limitations

A fundamental limitation of all the research work undertaken to date was the small range of steel compositions examined. While a second limitation was the thermal conditioning of the test samples. McCreery (1984) studied quench and tempered SAE 8620; Brunet (1985) researched normalized SAE 1045; Rittgers, Frost, Krauss, and Matlock (1989) examined quench and tempered SAE 4140; while Morris, Ryalls, and Wade (1991), and Fattorini and Grifoni (1990) studied several European steel grades with different heat treat conditions. Although the work of Morris, Ryalls, and Wade (1991) as well as Fattorini and Grifoni (1990), was the most comprehensive, they did not cover a broad range of steels or heat treat conditions. A third limitation was the lack of complete characterization of the test material with regards to cracks, porosity, non-metallic inclusions, and other defects. None of the investigators reviewed were able to correlate the size and distribution of defects in the as cast material with those found in the specimens of various reduction levels. However, Morris, Albiston, and Igham (1990) fabricated samples for laboratory investigation. These researchers drilled holes in the material to simulate central porosity and subsequently observed the change in the shape of the defects as the material was hot worked. They quantified the amount of welding or consolidation of the defects and related that to the degree hot reduction.

CHAPTER 2. REVIEW OF RELATED LITERATURE

Characteristics of Continuous Cast Steel that Affect Mechanical Properties and Fatigue Performance

Different researchers have focused on different aspects of the problem. Wells (1962) was interested in relating the properties develop by testing minimally reduced ingot cast material to continuous cast steel with similar degrees of reduction. Wells (1962) was interested in the relation between hot working and the subsequent effect on ductility and toughness of steel. Eckel, Matthews, and Mravec (1972) measured the properties of steel produced from a new start-up continuous cast facility and compared them to those properties found in traditional ingot cast material. Hawbolt, Weinberg, and Birma-Combe (1979) recognized the need to control the size and distribution of defects in the material to be tested, as a result, they produced their test samples under laboratory conditions. These researchers were interested in the change in the size and distribution of defects found in continuous cast material after hot working. Baudry, Giroud, Duplomb, and Jacob (1991) investigated the properties of continuous cast steels with regards to their rolling contact fatigue life performance in bearing applications.

As outlined by Rittgers, Frost, Krauss, and Matlock (1989), the structure and properties of continuous cast steels are affected by several inherent characteristics of the material. These characteristics include: (1) chemical composition and segregation, (2) non-metallic inclusions, (3) porosity and voids, and (4) residual stresses. Industry has developed continuous casting methods and processing technologies to control these characteristics (Brunet, 1985). In part, electromagnetic stirring, shrouding, casting velocity, and degree of superheat are major continuous casting process parameters affecting steel properties. The final factor, and of prime interest in this study, is the effect reduction by hot rolling or other deformations processes has on a steels subsequent structure, mechanical properties, and fatigue performance.

Non-metallic Inclusions

It was shown by Farrel, Bilek, and Hilty (1983) that non-metallic inclusions have an adverse affect on the tensile strength and toughness properties of steel. From a fracture mechanics stand point, inclusions also have a strong influence on fatigue crack initiation and subsequent crack propagation. Farrel et al. (1983) indicated that fatigue properties are most strongly influenced by alumina oxides, glassy oxides, and oxide clusters formed by fragmented dendrites. These reoxidation inclusions are the result of oxygen pickup by the steel during liquid metal transfer from the tundish to ladle and between the ladle to mold. Shrouding the pouring stream with ceramic and inert gas shields may control this reoxidation. Baudry, Giroud, Duplomb, and Jacob (1991) investigated the effect non-metallic inclusions had on bearing pitting fatigue life. These researchers indicated that three different types of non-metallic inclusions where found at the origins of fatigue cracks. These inclusions were comprised of titanium nitrides, complex oxides, and sulfides. Baudry et al. (1991) established a relationship between inclusion size in the form of a radius and a specimens fatigue limit. They also reported a relationship between Hertzian stress and surface plastic deformation. Widner (1992) investigated the relationship between non-metallic inclusions in continuous cast steel and bearing fatigue. Widner (1992) developed a linear correlation between the total length of inclusions and fatigue life for various steel making practices. Speich and Spitzig (1982) found that tensile properties and Charpy impact strength of SAE 4340 plate steels decreased more rapidly when the volume fraction of sulfide inclusions was increased. They also found that changing the shape from an elongated form to a spherical configuration increased tensile ductility and impact strength. Tomita (1988) investigated the effect of hot rolling reduction on the shape of sulfide inclusions and the resultant change in fracture toughness. This researcher found that hot rolling significantly changed the shape of sulfide inclusions and improved plain strain fracture toughness. Leslie (1983) found in his research that the sum of the lengths of non-metallic inclusions in a specific volume of material was correlated the amount of impact energy absorbed. The higher the volume fraction of oxides and sulfides the lower the energy absorbed by the test specimen. Leslie (1983) also found that non-metallic inclusions are effective in initiating and propagating fatigue cracks. This researcher also demonstrated a correlation between increasing inclusion diameter and a lower percentage of reduction of area in samples tested. Leslie's (1983) research indicated that elongated inclusions could increase fatigue crack growth rates. However, Leslie (1983) found this may be less important than the role of inclusions in crack initiation. Finally, Leslie (1983) found that there was an excellent correlation between the damaging effects of inclusions in bearing steels and their thermal expansion coefficients. As a result of these and other studies, industry has shown extreme interest in the degree of hot reduction required to mitigate the deleterious effects of non-metalllic inclusions.

Porosity and Voids

A major structural feature of continuous cast steels that influences the mechanical properties and fatigue performance of the final product is porosity or more generally internal soundness. This feature has been characterized as porosity, voids, fissures, and central looseness with other defects being crack like. Morris, Ryalls, and Wade (1991) classified the porosity into three groups: (1) fine and continuous, (2) fish bone, and (3) spherical and distinct. Hawbolt, Weinberg, and Birma-Combe (1979) examined the effect of hot reduction on continuous cast steels with defects such as halfway cracks, which are the by-product of poor casting practice. These researchers found that in the billet cross-sections they examined the size and distribution of cracks and other defects varied appreciably along the length of the billet. Hawbolt et al. (1979) found that a given section of material could exhibit no residual cracks, or significant cracks, depending on the initial as cast structure. The occurrence and distribution of these defects is entirely random. Therefore, they are difficult to track and can be one of the fundamental problems of research in this area. Schultz, Moore, Krauss, Matlock, Frost, and Thomas (1993) investigated porosity in steel and found that a gradient in the porosity exists across the transverse sections of continuously cast billets. Porosity sizes and concentrations were lower near the surface of the billet and higher at the centerline. Porosity they found in steels was related to problems in feeding the liquid metal into the solidification interface and the entrapment of dissolved gasses in the solidification structure (Schultz et al. 1993). These researchers also found that the uneven growth of the advancing columnar zone or a minimal area of equiaxed grains trapped pools of liquid metal inside the solidified billet. As the liquid transforms to solid metal, contractions occur that forms the shrinkage porosity. Most clean, vacuum degassed steels produced by ladle metallurgy methods exhibit low concentrations of oxygen and nitrogen and gaseous shrinkage is not a factor in the evolution of porosity. Schultz et al. (1993) found that specimens containing a high density of large sized pores exhibited an inferior fatigue life when compared to samples containing a low density of small sized pores. These researchers found that porosity lowers strength by increasing the net section stress due to decreased cross sectional area and by developing a tri-axial stress sate at the site of the pores. They also found that porosity can act as crack nucleation sites during the first fatigue cycles. Therefore, porosity decreases the time required for crack initiation and propagation. Baudry, Giroud, and Duplomb (1991) reported studies by the French government research institute that drew the following conclusions for an AISI 1045 steel: (1) it can be verified that the major area of porosity is located in the equiaxed zone, and (2) a reduction ratio of 4:1 is enough to recover mechanical properties (tensile) after a normalizing heat treatment. Thus, many researchers have interest in and investigated the degree of hot reduction or deformation required to completely weld these internal pores and fissures.

Segregation

Schauwinhold (1982) found that the presence of centerline segregation in continuously cast steel lead to a reluctance by many industrial customers to utilize continuous cast steel. This prompted Schauwinhold (1982) to investigate the meaning of this phenomenon as it related to the properties and performance of continuous cast steels. The focal point of the study by Schauwinhold (1982) was: (1) the investigation of transverse or cross sectional properties, (2) weldability, and (3) fatigue strength. The subsequent investigation revealed that the normal center segregation did not have a detrimental effect on the transverse material properties of the steels examined. Brunet (1985) found that the degree of segregation decreased in relation to the increase of the equiaxed area. Expanding this equiaxed crystalline region by electromagnetic stirring (EMS) was developed as a method to minimize segregation. EMS has an effect on the dendrite morphology or dendrite arm spacing. Stirring breaks down dendritic growth and promotes equiaxed grains (Islam, 1989). Wojcik (1982) indicated that improper casting conditions, caused by very high casting temperatures and the resulting steep temperature gradients within the solidifying billets, lead to the development of a pronounced columnar dendritic structure. This condition was associated with the formation of central zones of variable positive carbon and sulfur segregation. Wojcik (1982) indicated the presence of this center segregation increases structural non-homogeneity of the cast billets and the products rolled from them. This condition can have deleterious effects on manufacturing processes such as heat treatment.

Residual Stresses

Preston (1991) researched the effect of steel making practice on fatigue strength. In particular, he investigated the differences in the fatigue limit he found between two different steels. Preston (1991) found the anomaly could be explained by the difference in residual stress found in steel A and steel B. Residual stresses will increase or decrease the applied mean stress depending on the tensile or compressive nature of the residual stress. Leslie (1983) found that significant residual stresses developed in the iron matrix surrounding non-metallic inclusions due to differences in the physical properties of the inclusions and the surrounding matrix. Leslie (1983) found the properties affected by non-metallic inclusions included the coefficient of thermal expansion, elastic constants, and plasticity properties.

Continuous Casting Methods or Production Processes that Affect Mechanical Properties and Fatigue Performance of Steel

In continuous cast steel products, the solidification microstructure between the surface and the central axis of the product consists of three distinct zones (Brunet, 1985). Zone one, called the chill zone, is near the surface and consists of a fine grained columnar structure. Zone two, called the columnar zone, extends from the chill zone and is characterized by long dendrites with primary axes normal to the mold surface. Zone three, called the equiaxed zone, comprises the remainder of the section with a structure that is randomly orientated equiaxed dendrites. To reduce the extent of centerline porosity and segregation, the columnar zone is minimized and the equiaxed zone is maximized. Brunet (1985) and Islam (1989) detail the methods and processes utilized to produce this effect.

Electromagnetic Stirring

Electromagnetic stirring (EMS) is utilized to improve the surface and internal quality of continuously cast steel (Islam, 1989). This stirring may occur in the mold or the solidifying strand in the final stage of the casting sequence. Rittgers, Frost, Krauss, and Matlock (1989) stated that EMS is utilized to modify the internal structure of the cast billet. These researchers found EMS promotes the formation of equiaxed grains and decreases the region of columnar dendrites by breaking off the dendrite arms as they grow. Fattorini and Grifoni (1990) found that electromagnetic stirring resulted in smaller pores or porosity that were more evenly distributed in the equiaxed zone. This permitted the porosity to be more readily welded by hot reduction and promoted satisfactory mechanical properties at lower reduction ratios.

Shrouding

During the continuous casting of steel, a major source of contamination is the reoxidation by air infiltration of the molten stream of steel in the transfer of material from ladle to tundish and from tundish to mold (Islam, 1989; Irving, 1993). This contamination results in deleterious non-metallic inclusions such as alumina oxides, which can reduce mechanical properties and fatigue life (Leslie, 1983). Because of the expensive problems caused by non-metallic inclusions, industry has developed ceramic shrouds between the ladle and tundish with argon injection as a means of minimizing air infiltration by providing a neutral atmosphere around the cast strand (Islam, 1989).

Between the tundish and mold a submerged entry nozzle in conjunction with the use of mold powder provides the necessary protective shrouding.

Casting Velocity

Casting velocity or the rate of removal of the cast billet from the mold has a significant effect on the extent of the equiaxed zone (Brunet, 1985). The combination of low casting velocity and electromagnetic stirring further increases the extent of the equiaxed zone and therefore lower segregation and finer distribution of porosity. Casting velocity and strand cooling rates can have an effect in the production of defects such as halfway cracks.

Superheat

Brunet (1985) found that the extent of the equiaxed zone is dependent on the degree of superheat of the molten steel in the tundish. Superheat is defined as the difference between the actual molten steel temperature and the steel temperature at the beginning of solidification within the billet. Brunet (1985) found that the higher the superheat the smaller the equiaxed area. Brunet (1985) established a relationship between the incremental increase in superheat and the subsequent equiaxed area. He demonstrated this relationship with and without electromagnetic stirring. This researcher also established a similar relationship with casting velocity. Generally, low superheat and low casting velocity permit a refined structure. Fattorini and Grifoni (1990) found that higher superheat values result in more extensive levels of internal porosity. They also found that the quality of quench and tempered steels was affected by the extent of superheat. These researchers stated that high superheat values produced larger interdendritic segregation that affected hardenability of the material. They indicated this segregation could also modify the fracture mechanism, thereby causing local material splitting and thus higher brittleness.

Effects of Reduction by Hot Deformation on the Mechanical Properties and Fatigue Performance of Continuous Cast Steel

Eckel, Matthews, and Mravec (1972) found that their tests on alloy steels indicated that continuous cast material was comparable to ingot cast material in macroetch ratings, non-metallic inclusion ratings, hot workability, longitudinal mechanical properties, and rotating bending fatigue strength. They also found that continuous cast material was superior in carbon control, surface quality, and transverse impact strength. They examined material that was vacuum degassed prior to casting and was hot worked to a reduction ratio of 6.6:1.

Wojcik (1982) investigated ingot and continuous cast material with reduction ratios of 13:1, 20:1, and 500:1. This researcher found that the percent reduction had the following effects. Higher reduction in area during forge rolling (20:1 versus 13:1) improved the torsional fatigue performance as well as the bending fatigue performance of continuous cast steel.

The reduction levels investigated by Eckel, Matthews, and Mravec (1972) and Wojcik (1982) may not have been low enough for these researchers to find evidence of a difference between continuous cast and ingot cast material.

Morris, Albiston, and Ingham (1990) conducted rolling tests with continuous cast billets at reduction ratios up to 20:1 to examine the evolution of both porosity and mechanical properties. These researchers found that the homogenization of tensile ductility was achieved at reduction in area of 4:1 to 6:1. Morris et al. (1990) went on to indicate that it can not be assumed that porosity has been completely eliminated even when full mechanical properties have been obtained at the centerline of the bar, since they observed a remnant of porosity for reduction ratios up to 15:1. These researchers concluded that, given the demanding applications of the final product a more sensitive evaluation criteria, other than tensile ductility, was needed.

Morris, Ryalls, and Wade (1991) conducted a series of deformation trials of continuous cast steels to investigate the effects that several unique deformation processes had on the consolidation of centerline porosity. The hot working or deformation processes they investigated were hammer forging, continuous forging, flat rolling, and groove rolling. Morris et al. (1991) found that hammer forging resulted in fullest degree of consolidation at the lowest area of reduction. That reduction ratio being 3:1. Flat rolling required a minimum reduction ratio of 5:1. While continuous forging and groove rolling required reduction ratios of between 5:1 to 7:1. These researchers also found that the reduction ratio required to achieve complete consolidation also varied with chemical composition. The alloy steels (SAE 8620 and 16MnCr5) required greater deformation than the carbon manganese steels (ST37-2, En5A, and En9). It was suggested, by Morris et al. (1991), that the alloy additions in SAE 8620 and 16MnCr5 may in some way hinder the healing or welding of the open pores or porosity.

Brunet (1985) found the following hot deformation processing factors were important contributors to the final properties of continuously cast steel. The first parameter was the temperature gradient that occurs within the product cross-sections during hot working or rolling. The second factor concerned the extent of the individual degree of reduction of each mechanical reduction stand on the production line and the rolling speed of the operation. The final factor consisted of the over-all deformation, which includes the final reduction ratio as well as any subsequent hot working such as forging.

Brunet (1985) cited several industrial studies stating, " Volkswagen found no difference in the fatigue strengths of axle spindles made from ingot cast and continuously cast chrome-boron steels in reverse bending stress tests. Opel reported similar results in reverse torsional stress tests on induction hardened axle shafts made from AISI 1035."

Brunet (1985) goes on to relate the importance of rolling temperature and speed on mechanical properties. The researcher describes a process that consists of high product temperature and slow rolling speed combined to enhance the internal welding of the pores. Brunet (1985) relates the effect the P (pass) parameter has on the core stress and subsequent properties of rolled steel. P is described by the following formula.

$$P = (e_1 + e_2) / 2 \, [\, R(e_1 - e_2)]^{1/2} \qquad (1)$$

Where e_1 and e_2 are the thickness of the product before and after rolling and R is the mechanical rolling cylinder radius found in the rolling stand. Therefore, heavy passes with large radius cylinders (small P) favor the crushing of pores in the heart of the product. High rolling temperatures also promote the welding process. Brunet (1985) cited other investigations that included electromagnetic stirring in combination with the P parameter. It was found that a reduction ratio of 2.2:1 was sufficient to recover core properties when the steel was EMS stirred and was rolled under heavy passes. Brunet (1985) found a ratio of 3:1 was enough to produce satisfactory structure and properties, if there was EMS no matter the P factor. And a ratio of 4.3:1 recovered the properties without EMS no matter the P factor.

Dyck, Frost, Matlock, Krauss, and Heitmann (1989) found that a reduction ratio of 7:1 was adequate to establish that no adverse effect could be found from any casting or solidification defect on the mechanical or torsional fatigue properties of microalloyed steel. Any variations that did exist they attributed to microstructural changes associated with the different cooling characteristics of bars with different diameters. They state this phenomenon is a characteristic of microalloyed steels. These researchers found that yield and ultimate strength of continuous cast microalloyed steel bars increased while impact strength decreased with increasing hot reduction ratio. Dyck et al. (1989) found that while the torsional fatigue strength is lowest at the 7:1 ratio, it is essentially consistent with all specimens of 10:1 or greater area of reduction.

Rittgers, Frost, Krauss, and Matlock (1989) determined that torsional fatigue crack initiation sites change with changing reduction ratios. The researchers found that that the as cast and 2:1 reduction ratio material developed fatigue cracks in regions that reflect the residual solidification structure. They found that for high stress (low cycle fatigue) cracks initiated at interdendritic regions or at columnar grain boundaries. For low stress (high cycle fatigue) samples cracks started in the micro-pores. Rittgers et al. (1989) also found that for both the high and low cycle fatigue of all of the 10:1 and some of the 4:1 reduction ratio specimens developed cracks at clusters of oxide inclusions.

They concluded that the hot reduction ratio seemed to have little influence on the number of fatigue cycles required to initiate a crack. However, once a crack was initiated the lower reduction ratio material fails in a much shorter time frame than the heavily reduced material.

Baudry, Giroud, Duplomb, and Jacob (1991) found that the rolling contact fatigue endurance level of bearing steels produced by continuous casting were at least equivalent to ingot cast steel. These researchers did not cite a minimum acceptable reduction ratio.

Schultz, Moore, Krauss, Matlock, Frost, and Thomas (1993) found that fatigue samples produced from steel with reduction ratios of 3.3:1, 5:1, 9.9:1 and 46:1 exhibited very similar fatigue life properties when subjected to fully reversed axial testing. These researchers also discovered that the strain hardening behavior could also be used to rank with respect to reduction ratios. They found the 46:1 reduction ratio samples displayed the lowest cyclic strain hardening while the 3.3:1 samples exhibited the highest level of strain hardening. Finally, they concluded that the reduction ratio needed to produce the required performance was achieved at a ratio of 5:1.

Tomita (1988) investigated the effect hot rolling had on sulfide inclusions and subsequent mechanical properties of SAE 4340 steel. This investigator found that hot reduction by rolling improved plane strain fracture toughness in the longitudinal testing orientation as well as tensile ductility and impact energy levels. Tomita (1988) did not cite a minimum acceptable reduction ratio.

Hawbolt, Weinberg, and Brima-Conbe (1979) found that laboratory hot rolling tests indicated that a reduction ratio in excess of 6:1 was required to effectively close halfway cracks, the result of poor casting practice, in the continuous cast material. This degree of reduction was required whether the test specimen was oriented parallel or perpendicular to the rolling plane. These researchers also stated that an examination of the as cast billet and the commercially hot rolled bar, produced from the same continuously cast heat, revealed that the vestiges of cracks were still present after a 4:1 reduction. They go on to indicate that, since the size and severity of defects varies along the length of the billet, it was not possible to make a direct correlation between defects remaining in random samples of hot rolled bar and those originally present in the as cast billet.

In summary, we have seen from the studies, a variation exists in the hot reduction ratio required to produce properties consistent with ingot cast steels. It appears that continuous cast steels approach the structure, mechanical properties, and fatigue performance typical of more the heavily worked ingot cast material after relatively small amounts of deformation. It appears that the benefits of continuous cast steels can be applied in some design applications. The greatest concern is when small as cast billets are used to produce large bars for applications such as axles. For these situations, great care must be exercised in the selection of a continuous cast steel product. Thus the hot reduction ratio is one of many parameters that must be specified and controlled when attempting to assure the consistency of the properties of continuous cast steel. The same level of product integrity and reliability, as ingot cast material, can be obtained at lower reduction ratios when other key parameters such as electromagnetic stirring, casting velocity, shrouding, and superheat are utilized and properly controlled to minimize porosity, cracks, segregation, and non-metallic inclusions.

Evaluation Techniques that Provide an Indication of the Evolution of Internal Soundness, Structure, and Properties

Brunet (1985) stated that the techniques utilized to characterize the effect of hot working on continuous cast steel structures and to measure subsequent mechanical properties might include tensile properties such as ultimate strength, reduction in area, and percent elongation. Other researchers utilized rotating bending and torsional fatigue tests, scanning electron microscope (SEM) studies, and gamma ray absorption studies to measure porosity.

Of the mechanical properties examined by Morris, Ryalls, and Wade (1991), the variations in area of reduction best represented the evolution of internal soundness for reduction ratios of 7:1 or less. For higher reduction ratios the Charpy impact test is more sensitive indicator of the level of internal soundness. However, Morris et al. (1991) found that at least ten Charpy test samples were required to produce a statistically significant representation of the level of consolidation for a given reduction ratio. Dyck, Frost, Matlock, and Krauss (1988) were interested in the torsional fatigue characteristics of microalloyed steels in automotive axle shaft applications. These researchers supplemented those tests with Charpy impact and tension testing. These researchers found that with an increasing reduction ratio the hardness, yield strength, and ultimate strength increased. They also indicate these results are consistent with the microalloyed family of steels. This phenomena is the result of the manufacturing processes causing different cooling rates for different sized bars during production.

Eckel, Matthews, and Mravec (1972) utilized macroetch ratings, no-metallic inclusion ratings, end quench hardenability tests, hot twist tests, and Charpy impact tests in addition to tensile and rotating bending fatigue tests to characterize material. These researchers were interested in brittle-ductile behavior, cyclic load behavior, and hot workability.

Baudry, Giroud, Duplomb, and Jacob (1991) investigated the useful life of bearings subject to rolling contact fatigue. They utilized a flat washer method of testing the material. The test consists of ball bearings rolling in a circle on a flat washer with a 4.17 GPa contact stress and the washer rotating at 1500 revolutions per minute. Baudry et al. (1991) examined specimens from various longitudinal and transverse sections of bar and tube.

Emerick (1962) examined and compared continuous cast and hot rolled ovals, rounds, and tube for porosity and crack closure. The evaluation methods consisted of macroetch ratings, tensile strength, yield strength, elongation, and reduction of area.

Fett and Ross (1991) utilized tensile tests, Charpy impact tests, and rotating bending fatigue tests. These researchers found the only properties affected by reduction ratio were ductility as demonstrated by reduction in area, elongation, and Charpy tests.

Stovar and Kolarik (1987) utilized ultrasonic inspection techniques to determine the extent, size, and distribution of non-metallic inclusions in bearing steels. Ultrasonic signals reflected from inclusions that exceeded a threshold value were recorded and mapped on the rolling contact fatigue test surface. Stovar and Kolarik (1987) were able to develop an ultrasonic inspection method that could be used to quantify the inclusion content and correlate that with the fatigue life of bearings.

As pointed out by Hawbolt, Weinberg, and Brima-Combe (1979), any evaluation method must take into account the size and distribution of defects such as porosity, non-metallic inclusions, and cracks as they very along the length of the product to be examined. The optimal characterization technique would be unaffected by the random nature of the anomalies found in the as cast and deformed material and would be able to track those defects as the material is processed.

Morris, Ryalls, and Wade (1991) found that the Charpy impact test is sensitive with respect to the remnant porosity in the test piece. They speculated that this sensitivity was the result of V-notch being acutely affected by porosity. They go on to indicate that the Charpy test is sensitive to the direction in which the test specimen is obtained as well. Thus, both transverse as well as longitudinal test samples must be evaluated.

In summary the percent reduction in area and percent elongation from tensile tests and Charpy impact tests appear to be the most sensitive evaluation methods of differentiating material subject to reduction by hot working.

Evaluation of Research Design and Experimental Methods

Baudry, Giroud, and Duplomb (1991) utilized accelerated high load and high speed rolling contact fatigue tests to simulate bearing applications. These researchers examined specimens taken from different areas of the test material (inner, middle, and outer sections) and they tested both transverse and longitudinal samples. This permitted them to analyze the effects of reduction ratios and material defects by location and direction in the test samples. The experimental design consisted of two steps, (a) a flat washer test and (b) a test of fabricated bearing components. In the experiments they controlled geometry, lubrication, temperature, and other factors so that those factors did not affect the experimental outcome. The researchers fabricated the washers and bearing components from the same heat of steel. Therefore, they were not able to fully investigate the material variations that can be found in different heat lots of steel. These investigators examined only one level of material reduction in both the ingot and continuous cast steel. Therefore, they could not predict the existence of some minimum level of continuous cast steel reduction required to develop equivalent properties to ingot cast steel. Since the area of study was very narrow and specialized, the findings could not be readily extended to a broader range of applications.

Dyck, Frost, Matlock, Krauss, and Heitmann (1989) examined a specialty steel (10V45) that is not a primary material utilized by most engineering designers. They confined their study to this material and did not evaluate other steels. The properties of the microälloyed steel they studied were affected by the processing methods utilized to produce it. This lead to the investigators finding that the property differences found were related to microstructural differences developed by uncontrolled cooling rates during the fabrication of the different test bars. They found the smaller bar diameters cooled more rapidly producing finer grain structures. In the experimental design the researchers failed to control the cooling rates of the bars as they were processed; this caused the validity of their study to be in question. Although they tested five levels of reduction, they did not examine material with 2:1 or 3:1 reduction ratios. This indicates that their data may fail as a predictor of properties in lower levels of material reduction. These researchers obtained their specimens from the columnar zone of the material in a longitudinal direction. Since they did not take sample from multiple locations or in the transverse direction, they may have failed to find significant effects on the material properties in those regions. These researchers developed a special torsional fatigue testing apparatus and, therefore, were in a new area of research that could not be supported by past investigations.

Fett and Ross (1991) examined two of the most widely used engineering steels (AISI 8620 and AISI 4140) to evaluate the effects of reduction by forging on the properties of these steels. They tested as cast billets and five levels of reduction produced by forging. The forging forces were applied perpendicular to the axial direction of the billet. Since the fabrication method may not produce the same degree of consolidation as manufacturing production rolling operations, the data collected may not be directly applicable or correlate to production operations. These researchers fabricated test samples from the mid-section of each test specimen for tensile, Charpy v-notch, and rotary bending fatigue tests. Fett and Ross (1991) did not attempt to determine the metallurgical characteristics, such as porosity and inclusions, of the particular heat of steel they studied. As a result, they could not evaluate the quality of the steel they examined. As was outlined earlier, many material characteristics can affect the properties of steel. The researchers also did not control the production process or determine the manufacturing method for this particular heat of steel they examined. Therefore, Fett and Ross could not relate their findings to the quality of the material they examined.

Hawbolt, Weinberg, and Birma-Combe (1979) evaluated the effect hot reduction had on continuous cast steel containing known cracks that were the result of uncontrolled and excessive process variation. These initial "halfway" cracks were compared with those found at various levels of hot reduction by forging. They examined four different heats of steel of different chemical compositions. In addition to observing the effects on crack closure they also measured tensile properties at -196 ° C to maximize the effect of small defects on the test results. These researchers tested a control heat of steel, one that contained no known cracks, in addition to the four test lots that contained cracks of varying degrees. This gave them a baseline material to evaluate and compare the effects that cracks of various dimensions have on specimens of various reduction ratios. One of the principle problems with the study was the inability of the researchers to correlate specific defects before and after reduction and their affect on the properties of the specimen. These investigators utilized a laboratory rolling as a means controlling the material under test. They subsequently compared the material produced in the laboratory with steel produced by conventional manufacturing processes. This permitted them to make some predictions regarding the effects of cracks on production material based on experimental data derived from their study.

Morris, Ryalls, and Wade (1994) developed a research program to investigate the degree of reduction required to (a) consolidate central looseness and voids, and (b) develop material properties suitable for end use in industrial applications. The goal of these researchers was to devise a means of predicting the effects of various deformation parameters on the defects listed above. Thus these researchers delaminated their study by indicating they would not explore the effects of steel making and casting variables and practices. However, they did recognize the influence that these variables had on their study. Five different steel grades were selected for examination. The steels tested consisted of plain carbon and alloy compositions with high and low carbon contents. They assumed that these five grades would be representative of the population of solidification structures found in commercially produced continuous cast steel. Morris et al. (1991) investigation involved a theoretical study to model, by finite element analysis, the effects of different deformation geometry and production practices. Next, these researchers conducted an experimental study to determine the effects of various deformation processes on the structural refinement of the subject material. Finally, the subject material was characterized for pore or void content, segregation, inclusion population, and microstructure.

Rittgers, Frost, Krauss, Matlock, and Wei (1989) investigated the torsional fatigue resistance of a continuously cast heat of AISI 4140 steel. These researchers recognized the influence that casting and processing parameters had on the material properties they were investigating, but did not incorporate that realization into their study. They extracted tensile and fatigue specimens from only the columnar zone parallel to the longitudinal axis of the product under examination. Therefore, they did not have data on the equiaxed area of the product or information in the transverse direction. As has been shown, the equiaxed area is a prime location for segregation and porosity. Although they reported examinations of as cast steel products reduced by 2:1, 4:1 and 10:1 ratios, the material with the 2:1 degree of reduction was not exhibited in the data. The region of 2:1 to 4:1 reduction is the critical area of interest; however, the authors did not address it. Rittgers et al. (1989) made an extensive qualitative and quantitative examination of the non-metallic inclusion content of the test material, but did not relate that data to the principle subject of their investigation and how it affected the outcome of those tests. The torsional fatigue testing conducted was a mixture of load control and stroke control, which may have affected the interpretation of the final results. In general these researchers did not characterize the material under investigation by ultrasonic inspection or gamma-ray , as has been done by other researchers.

Schultz, Moore, Krauss, Matlock, Frost, and Thomas (1993) developed and implemented an excellent experimental design and research method. The research problem was defined as the determination of a minimum reduction ratio for a high strength martensitic steel (hardened AISI 4140) subject to fully reversed axial fatigue tests. In addition they examined the affects that manufacturing process control and specimen location within the test product had on the derived data. They developed a test specimen matrix that included (a) manufacturing process control parameter, (b) specimen location within the product, (c) specimen orientation, and (d) thermal processing. These researchers held many of the steel melting and casting parameters constant except for the application or removal of electromagnetic stirring. Test specimens were removed from the columnar impingement, columnar dendritic, and equiaxed zones in the material. These researchers found that a reconfiguration of the fatigue test specimen was required when the parts failed at an undercut, a feature detailed in ASTM standards. The undercut acted as a stress raiser and negated the effects of any difference in material properties. They developed an hour glass shape for the test sample and collected new data. These investigators were able to demonstrate a direct relationship between ductility and the steel porosity content. Specimens containing a high density of large sized pores exhibited poor ductility on the order of 0.9% to 1.1% total elongation. While specimens containing a low density of small pores exhibited total elongation of 3.8% to 11.4%. They also found that in the as cast specimens fatigue cracks initiated at surface porosity in all specimens. They were able to relate porosity size and distribution to fatigue life.

CHAPTER 3. CONCLUSIONS AND FUTURE RESEARCH

Past research does not provide adequate information in identifying a universal minimum reduction ratio, for continuous cast steel versus ingot cast, that will provide confidence to the design community that mechanical properties and fatigue performance can consistently be met under all circumstances. As has been shown, many parameters of the steel production process must be taken into consideration in addition to the ratio of hot reduction. Among others, the melting and casting parameters of superheat, electromagnetic stirring, shrouding, and casting velocity must be well defined, specified, and controlled. Other important factors that must be specified and controlled are the hot reduction process procedures. For example, the temperature gradient across the product thickness during rolling must be well defined and controlled. In addition, the reduction ratio of each rolling pass, the rolling speed, and the final total reduction ratio must be detailed. In summary, the over-all deformation of the product in the form of additional rolling and forging must be considered.

As has been shown, many of the physical properties of continuous cast steel affect its final mechanical and fatigue performance. The importance of non-metallic inclusions has been outlined by many researchers. Non-metallic inclusions have a significant effect on crack initiation whether by fatigue or fracture. Non-metallic inclusions also assist in propagating cracks by providing linkages for crack fronts as they move through the material. The type and size of the non-metallic inclusions are important to the final properties and performance of the material in end use applications. Alumina oxides have been found to be the most detrimental. Thus, processing methods must be specified to control the type, size and distribution of non-metallic inclusions. The effectiveness of any continuous casting and hot reduction process will be the degree to which non-metallic inclusions are broken up and their deleterious effects diminished.

Porosity has certainly been shown to have a deleterious effect on mechanical properties and fatigue strength. The size, degree, and distribution of pores all have an effect on lowering a materials performance in a given design application. Thus, the degree of hot reduction required to weld the porosity is dependent upon the size, density, and distribution of the incipient pores. As a result, a universal reduction ratio can not be defined unless it is for the worst case condition or for a process controlled so that a characteristic porosity can be statistically predicted. Again, processing methods must be specified to control the size, density, and distribution of porosity.

Investigators have not been able to correlate the effects of defects in a given volume of steel before and after hot reduction on the materials subsequent performance. The size and distribution of defects vary widely over the length of the test material. For a particular random sample of material, an examination could exhibit no residual defects or many defects. Because of this, it is difficult to establish directly the amount of hot reduction that is required to insure the integrity of continuous cast steel. An alternate approach would be to closely control process parameters to minimize deleterious defects.

Future research must take more factors into account in defining a minimum reduction ratio. A matrix of process parameters and material conditions must be developed to assess the contribution each factor has on defining what that minimum hot reduction ratio is for a given product and final application. These parameters would include, at a minimum, the degree of superheat, the type and extent of electromagnetic stirring, the type and degree of shrouding, and casting velocity, A more precise definition and description of the test sample must be developed. For example, porosity may be rated by some method such as gamma-ray absorption, inclusions characterized by ultrasonic density, residual stress measured by laser holography, and other non-destructive inspection methods to be developed in the future. Thus, a specific steel mill utilizing well defined processing methods may claim a minimum reduction level will yield continuous cast properties equivalent to ingot cast given specific levels of porosity, non-metallic inclusions, and other defects in the as cast structure.

A factor that was not considered by any of the researchers, other than Brunet (1985), was the actual load history that the final product is subjected to in service be used to test the material. Future research should include tests utilizing load histories from actual applications. Finally, part of any qualification procedure for a specific steel mill and the subsequent development of a specific minimum reduction ratio may involve actual component testing by the customer.

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