Client Oriented Quality

Metallurgical Technologies

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1. **Introduction**

Metal products for ship building and the offshore industry are delivered under contracts between the client (i.e. shipyard) and manufacturer (i.e. metallurgical plant). This contract usually contains a section that regulates the quality of products and methods of control. Also in this section there are specified check points that the client can use prior to accepting the product. In most cases, before signing the contract the buyer verifies the supplier meets the quality assurance standards, as well as technical manufacturing program requirements for this or similar products. These documents include references to standards and certifications, which characterize the process and use of the material. Today, most aspects of the relationship between supplier and buyer in terms of product quality and ways of its control, especially in the market of metal products for ship building and the offshore industry, have been already standardized and (or) based on precedents. In addition, these relationships are controlled by specific regulatory authorities and the final user. The introduction of additional terms in the contract usually leads to an increase in the production cost or is a criterion for supplier selection.

Thus, the purchase of steel for ship building and the offshore industry is based mainly on information from the manufacturer. On the other hand, the buyer of steel products is focused on the standards. While the standards contain mandatory requirements, additional requirements are established in the agreement between buyer and seller. Without having all this data from the start, the buyer is disadvantaged, because he doesn’t have enough objective information on the influence of quality indicators of products on meeting their needs. This limits the ability of the buyer to establish additional requirements on the product quality.

Example: the standards for steel sheets, ASTM A 6 / A 6M - 00a, EN 10025, GOST 1577 provide a different positioning of the specimens for mechanical testing. At the same time, in some cases specimens may be cut from ¼ thickness of the plate. The relatively long service life of metal products, used in ship building and the offshore industry, and rapid development of metallurgical technology (use of new steel grades, modes of deformation and heat treatment, welding, machining, etc.) does not give the buyer the opportunity to gain a representative database on the influence of properties (regulated by standards and (or) the contract) on operating efficiency of the product. Possible disadvantages of quality of metallurgical products, caused by metallurgical technology, are compensated using the safety factor in the sizing of products. This safety factor allows reducing possible risk of accident and reducing the liability of the manufacturer.

The objective of the program «Client oriented quality» is to provide the buyer with objective information on the impact of the elements of metallurgical technologies on satisfying the client requirements on the product quality and optimizing the production cost.

The following materials are based on the author’s experience and illustrate the influence of the main elements of metallurgical technology on the metal quality, as well as detection of defects and probability of defects occurrence.
2. **Metallurgical technology and product quality**

2.1. **Product quality**

In this paper, we will not consider the influence of geometric dimensions on the quality of products. This indicator of quality is the most easily controlled. Today, in principle, all manufacturers of metal products are able to provide the required accuracy of the geometric dimensions of the product. On the other hand, the quality indicators based on the properties of the metal will eventually determine the efficiency of metal products usage. These indicators are not easy to verify, but they depend on the strength, including long-term strength, plasticity, corrosion resistance, etc. The key to these quality indicators is the structure of the metal. In addition, each stage of the metallurgical technology adds potential new defects typical to that stage.

If we consider the metallurgical technology as part of a chain process to meet customer’s needs for high quality products (Fig. 1), the first link in this chain is the quality of raw materials, and the following link - the quality of service, which includes packaging, shipping, financial services, etc.

![Fig. 1 Metallurgical technology quality process](image)

The quality of raw materials is an important element of metal products quality to a greater extent for the manufacturer. Low quality raw materials, such as the ones polluted with unwanted elements, require cost increases during smelting process. In principle, modern metallurgical technologies have a great degree of control that allows conforming to the quality of the raw material with a required chemical composition and purity of the metal.

Semi-finished products discussed in this paper are:

- flat products;
- bar, rod products;
- Tubular products.

On the other hand, if we consider the impact of metallurgical technology on the structure of metal and the risk of defects, we can distinguish three main factors that determine the quality of the metal:

- Chemical composition;
- Heat treatment mode (temperature of treatment);
- Deformation (deformation mode).

Therefore, more attention should be given to the processes where these three factors are present.
In general, the quality of steel is determined by four technological processes, which cannot be treated separately (Table 1):

**Table 1**

<table>
<thead>
<tr>
<th>Process</th>
<th>Brief description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid metallurgy, including steel casting</td>
<td>Chemical composition, Metal purity, content of elements and homogeneity of distribution, defects</td>
</tr>
<tr>
<td>Heat treatment of metal</td>
<td>The structure (type of obtained crystal lattice), size and shape of the grains, obtained properties, distribution of properties of product by thickness, internal stresses, defects</td>
</tr>
<tr>
<td>Deformation</td>
<td>The shape and sizes of product, defects, homogeneity of the metal structure, stresses</td>
</tr>
<tr>
<td>Mechanical Treatment</td>
<td>Surface quality, dimensional accuracy, local stresses</td>
</tr>
</tbody>
</table>

Widely used processes in ship building and the offshore industry such as welding affect the quality of the products. All the above factors, listed in Table 1, determine the product quality using fusion welding. For example, the operational characteristics are determined by the structure and properties in the heat affected zone (HAZ) of the weld seam.

The transformation from semi-finished metal to the finished product requires additional processing, which consists of the following:

- **Mechanical engineering** provides the design of the product and its performance. In addition, individual elements of this may influence the resistance of the metal to corrosion. For example, the presence of cavities in the design of the product may provoke an accelerated development of corrosion, which requires additional measures to protect the metal. Also, the correctly calculated construction can withstand loads using less metal.

- **Welding**, consisting of: welding parameters, selection of filler material, process & procedures, etc. For the most common welding processes, which involve the local melting of the metal, the process involves two of the above mentioned indicators that determine the metal quality - the chemical composition, which may change during the welding process, and temperature changes which may affect the metal structure and its properties. For example, the operational characteristics of the final product are determined by the structure and properties in the heat affected zone (HAZ) of the weld seam.

- **Machining**, consists of: cutting, drilling, turning, milling, grinding, etc. The process of machining, in principle, only affects the quality of the work surface and allows, if necessary, to remove the metal layers with issues. However, if the surface treatment is affected the quality of the tool can lead to local temperature rise and plastic deformation of the metal. An example is the appearance of temper colors on machined surfaces.

- **Material Protection**. The type of coating, its thickness and adhesion to the metal have to prevent the penetration of corrosive environment to the metal surface and avoid the development of corrosion. The quality of the metal surface is also a factor. For example, closed notches, which are the legacy of deformation or heat treatment, lead to the development of corrosion under the coating.

### 2.2. Strength and plasticity

Besides the geometric parameters and corrosion resistance (which will be discussed below), the following criteria are used to evaluate the quality of metal products:

- strength;
- resistance to deformation;
- plasticity
For the customer it is preferable that the same material would be both strong and plastic. This problem is being studied by the world's leading metallurgical laboratories. However, due to the nature of the metal today one must choose between strength and plasticity. Therefore, to select the standardized mechanical properties of the material, one needs to pay careful attention to the following indicators:

- Tensile strength
- Yield strength
- Elongation (contraction)

Mechanical properties indicators such as impact strength allow us to evaluate the quality of the metal structure on its ability to absorb impact energy.

The choice between strength and plasticity of the metal is quite complex. In this case producer and consumer have different points of view about these properties. This difference is due to the fact that the manufacturers want to protect themselves against possible claims. Let’s consider, for example, sheet steel for the components of drilling rigs. The desired and actual values of the mechanical properties obtained as a result of tension tests (Fig. 2) are shown in Table 2.

Table 2

<table>
<thead>
<tr>
<th>Index</th>
<th>Tensile strength TS, MPa</th>
<th>Yield strength Y, MPa</th>
<th>Elongation E, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required values</td>
<td>790…930</td>
<td>≥690</td>
<td>≥16</td>
</tr>
<tr>
<td>Obtained values</td>
<td>905</td>
<td>829</td>
<td>17</td>
</tr>
</tbody>
</table>

If we look from a formal point of view, the obtained values fall into the stated range. However, if we analyze these indexes from the point of view of the hypothesis that each material has a certain resource of plastic properties, which is determined by the ratio of tensile strength and yield strength (TS / Y) and allows further deformation (e.g. bending to give the desired shape) without destroying, then the best result is obtained when the yield stress is on the minimally acceptable level, and tensile strength on the maximum (curve 1, Fig. 2) (TS / Y = 1.35). A good result may be considered when the yield strength and tensile strength are at the lowest acceptable level (curve 2, Fig. 2) (TS / Y = 1.14). Curve 3 in Fig. 2 shows an acceptable result (TS / Y = 1.09) but also indicates that the resource of plastic properties it is almost exhausted. Further deformation, even a slight deformation, may cause microcracks that will be concentrators of stress and corrosion. The minimum level of residual plasticity is also confirmed by the minimum excess of elongation (17%) above the standard requirements which is (16%). Thus, we can see that the results meet the standard requirements, but the quality of metal is not as desired.

Also, it should be remembered that over time steel will be subject to aging, which leads to a slight hardening and a significant loss of ductility.
2.3. Forming of product quality

Meeting the requirements of standards and technical specifications for the finished product can be compared with parking in the garage. There are three potential problems:

- damaging the vehicle at the time of parking
- difficulties in exiting from the car
- difficulties departing the next day

The key to a successful parking is the speed and trajectory of the vehicle before parking. The same is for the steel products. Only in this case the trajectory is determined by the chemical composition of the metal, its purity, heat treatment and mode of deformation (Fig. 3).

![Fig. 3 Trajectory of mechanical properties](image)

The technological scheme provides a relatively stable quality of products within the stated standard requirements of the majority of metallurgical companies. However, very often for economic reasons, the company provides quality near the lower boundary of the requirements. This is due to the presence of certain technical contradictions in the production process. For example, the stiffness of the working stand of the rolling mill, which does not allow the company to manufacture products in a more narrow range of deviation from the nominal size, or the presence of mandatory oval cross-section of groove at lengthwise tube rolling or an increase in grain size of steel during the stabilization annealing of certain stainless steels.

Therefore, in many ways, the level of product quality depends not only on the actual results of measurements of physical quantities that characterize the quality, but also on the history of treatment, i.e., the set of equipment and technology organization. It is desirable that the existing equipment and technology assure that the quality of the product is in the vicinity of the lower boundary, and it has certain reserve in its capabilities.

Most claims about product quality occurred in those cases when the shortcomings of technology and equipment have been compensated for by treatment modes. The results are positive but, often rejected by the quality control. Therefore, for each specific case it is necessary to monitor the work of the equipment and to conduct an analysis of the technology. Then, based on monitoring results, controlled values and methods of control should be chosen.
3. **Metallurgical foundations of quality indicators**

3.1. **Liquid metallurgy and crystallization**

In the liquid state the metal has the properties of a liquid, but at this stage it is fairly easy to control its chemical composition by adding useful and removing harmful (for a given grade of material) elements. The main quality indicator here is the quantitative content of elements in a ladle and uniform distribution of these elements by volume of the ladle. Once the metal is crystallized, it is turned into billions of irregularly shaped crystals. A further set of deformation and heat treatment must ensure in the end the same uniform distribution of chemical elements not only from grain to grain in the product, but in each microscopic grain (Fig. 4).

![Fig. 4 Stages of liquid metallurgy technology and scheme of metal structure](image_url)

1 – Electric arc furnace; 2 – Ingot casting; 3 – continuous casting; 4 – examples of crystallized metal: A - shrink hole; B – column (dendrite) crystals; C – different sizes of crystals; 5 – elements of crystal structure
Non-fulfillment of this condition may result in appearance on the grain boundaries of strong and fragile structures - carbides (e.g. cementite) which are stress concentrators and may lead to cracks in the product. In addition, the concentration of alloying elements as coherent or incoherent structure inside grain in most cases also adversely affects the quality of the metal. On the other hand small defects inside the grain - dislocations, are alloying elements in atom that have a positive influence on the quality of the metal if they are distributed homogenously. At this stage there are a number of difficulties that are due to both the behavior of the metal and technology features.

In electric arc furnaces (1, Fig. 4) for uniform distribution of required elements in the entire volume of metal special melting process are used. Besides additional plant units for out-of-furnace treatment of steel, electroslag remelting is also used after the electric arc furnace. Their use is necessary in order to achieve the required distribution uniformity of chemical elements, removal of harmful elements, as well as cleaning of steel from impurities. At the casting stage (2, 3, Fig. 4) the liquid metal acquires a defined shape and becomes crystallized. After crystallization the direct control of the chemical composition of the metal becomes difficult.

Casting can be ingot (2, Fig. 4) or continuous (3, Fig. 4). Continuous casting provides a more stable quality and structure of the metal (4C, Fig. 4), but has some property limitations due to the volume of casted metal (steel should be killed), and due to the volume of the minimum melting volume of the same type of steel. Ingot casting technology allows casting of any steel grade, but is characterized by the fact that a shrink hole occurs in the top center of the ingot (4A, Fig. 4), which must be cut out. In reality, the exact depth of this shrink hole is very difficult to establish. Therefore, for example, 30% of the top of the ingot is required to be cut out according to the some process requirements. In fact, this value for a specific ingot may be too small or too large. Both processes, continuous and ingot casting, under certain cooling rates can provide a column (dendritic) structure of the metal (4B, Fig. 4). This structure provides a strong non-uniformity of chemical composition and properties and can further result in the destruction of the metal. It should be noted that this structure is more or less typical for the cast metal. Hot reduction (rolling or forging) is used after the casting in order to obtain a relatively circular shape and size of grain throughout the process.

An example of the crystal structure of the metal (5, Fig. 4) shows that at the stage of crystallization from a liquid or recrystallization in the solid state structure of the metal is filled with defects, some of which are located in the middle of the grain, and some at the grain boundaries. These structure defects are inevitable. However, a good quality metal is characterized by a relatively round grain of equal size in which the defects are uniformly distributed.

The influence of grain size on the properties of the metal should also be mentioned. In general, the smaller grain provides more resource of plastic properties in metal. Large grain reduces the plasticity and slightly increases the strength. For example, for heatproof steels a larger grain is recommended, and for heat-resistant a finer grain.

Failure to follow the technological process during the liquid metal and solidification stages leads to the occurrence of defects (Fig. 5), such as Axial porosity (1, Fig. 5) - accumulation of microscopic gas bubbles in the center of an ingot, failure to fill an ingot - Hole (2, Fig. 5), and uneven distribution of chemical elements over the cross section of an ingot - Segregation (3, Fig. 5).
The worst case scenario is when a defect is formed at the initial stages of technology process and goes unnoticed to subsequent stages. This leads to the fact that the local defect extends along the length of the product: Rolled bubble (1, Fig. 6), Blister (2, Fig. 6).

3.2. Deformation

Most of the metal products have deformation in their fabrication history. The physical basis of the metal deformation is the displacement of atom layers in the crystal relative to each other. In this process, the defects of the crystal structure of grain help the process (Fig. 7). They play the role of sources of displacement and reduce the force required to initiate movement. As a result of this displacement, the shape of grain changes and becomes more flat.

Similarly, due to the displacement of the dislocations in Fig. 7, the atoms of alloying elements, which were inside the grain, go to the grain boundaries. This leads to a distribution reorganization of chemical elements within the grains and deterioration in the quality of the metal.

In most cases, the deformation process is accompanied by heat treatment, which runs in parallel with the deformation process (hot deformation), or is carried out after deformation at room temperature (cold deformation). Thus, in the metal there are two processes that run in opposite directions: the deformation - flattens the grain, and squeezes out the defects towards its border, making it difficult for further deformation and breaking the uniformity of chemical composition, and on the other hand - under the recrystallization temperature the defects return inside the grain and restore the uniformity of chemical composition.

During the hot deformation process (Fig. 8) deformation and recrystallization are almost parallel, so the metal after such treatment is ready for further processing. The grains in it have a round shape, and chemical elements are distributed uniformly.
To ensure the metal quality during hot rolling it is necessary to monitor factors like the strain ratio (1, Fig. 9) and the process temperature. These factors provide a balance of grain flattening rates and return it to the round shape. In addition, an important role is played by the distribution of reductions on both sides of a square or a rectangle (2, Fig. 9), as there is a risk of the metal properties anisotropy.

The process temperature can be controlled using pyrometers. In addition, the stability of the metal pressure on the deformation tool may indicate the favorable balance of deformation and recrystallization. The increase in pressure may indicate that the metal temperature is not high enough.

Cold deformation can take place only under the plasticity of the metal, which in addition to chemical composition, is determined by the shape and size of grain, as well as the uniformity of distribution of defects and the chemical elements inside the grain, or in a general form - the quality of previous treatment. The difference (3, Fig. 10) between the tensile strength (1, Fig. 10) and yield strength (2, Fig. 10) decreases with increasing the degree of deformation. The intensity of this reduction depends on the mode of deformation - mainly from the distribution of reductions on both sides of the profiles, the diameter and wall thickness - for pipes, as well as the distribution of deformation along the passes during rolling of the sheet.

The increase in yield strength as an indicator of resistance to deformation requires an increase in strength for further processing. In addition, as the difference between the tensile strength and yield strength approach zero (TS / Y → 1) further impact on the metal would lead to destruction. This is due to the concentration of defects, squeezed out from the grains at their boundaries, as well as the flattened shape of the grain. In addition to increased strength, defects at the grain boundaries provoke intergranular corrosion.

Heat treatment after cold deformation is able to remove the residual stresses and return defects inside the grain and restore the form of grain. However, if during the deformation process, local microfractures had occurred in the metal, heat treatment cannot fix this. In addition, the grains are not only flattened after cold deformation, but also break up, which during subsequent heating can lead to an increase in their rate of growth and affect the metal quality.
3.3. Heat treatment

The energy transferred to atoms during heating is the basis of the influence of heat treatment on the properties and metal quality. This energy makes the atoms vibrate more in the crystal lattice. The frequency and amplitude of these fluctuations affect the mobility of lattice defects and atoms of chemical elements. Increasing the temperature to a certain level leads to the fact that the atoms change their position within the lattice, or break away from it.

Some materials, such as simple aluminum alloys after casting, form a certain type of crystal lattice, which remains unchanged throughout the temperature range. In this case, the effect of heat treatment on the metal properties and quality helps by removing the stresses and by recovery of round shape of grains. However, heat treatment of other materials such as steel in a solid state can change the type of crystal lattice (structure type). By their nature, each of the structure types has different properties that affect the properties of the product (Fig. 11). For example, the most important tool for managing the properties of steel is the effect of $\alpha \leftrightarrow \gamma$ transition. When the temperature drops to a certain value austenite (1, Fig. 11) decomposes into ferrite and cementite (2, Fig. 11). This process is reversible at heating. The advantage of austenite is its ability to contain within the crystal lattice defects, and many of the atoms of alloying elements, which ensures its plasticity. The solubility of elements in the ferrite is not so good, so they form carbides, in particular, Fe$_3$C - cementite - a strong and fragile phase.

![Diagram showing the influence of carbon content in steel and rate of cooling on the change in the structure of the metal](image)

### Table 1: Structure and Hardness HV

<table>
<thead>
<tr>
<th>Structure</th>
<th>Hardness HV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferrite</td>
<td>100-250</td>
</tr>
<tr>
<td>Austenite</td>
<td>300-650</td>
</tr>
<tr>
<td>Martensite</td>
<td>550-1.100</td>
</tr>
<tr>
<td>Cementite</td>
<td>900-1.200</td>
</tr>
<tr>
<td>Carbide W, V, Cr</td>
<td>2.200-2.700</td>
</tr>
</tbody>
</table>

Fig. 11 Diagram of the influence of carbon content in steel and rate of cooling on the change in the structure of the metal

1 – austenite; 2 – ferrite with different content of cementite: A - the carbon content of steel = 0.08%, B – 0.4%, C – 0.8%, D – 1.3%; 3 – martensite

The high cooling rate of austenite at heat treatment, called quenching, does not allow the lattice to readjust. The atoms of carbon and alloying elements are held tightly to form a specific structure - martensite (3, Fig. 11). This leads to high internal stresses and high strength of the product. The downside of high
strength, in this case is a low plasticity, distortion and the risk of cracking. Martensite is an unstable system. At heating, it decomposes into ferrite and cementite in accordance with the chemical composition.

Also the chemical composition affects the ability to change the type of crystal lattice. For example, the presence of sufficient amounts of nickel provides an austenitic structure that is stable at room temperature.

In terms of technology, heat treatment is an operation or sequence of operations through which the metal is subjected to one or more thermal cycles (heating, holding at temperature, cooling) within the required temperatures below the melting point to achieve specific properties.

**Heating** should not occur too quickly in order to avoid thermal stresses. Based on the heating temperature, the following types of heat treatment can be distinguished:

- Tempering - allows the removal of residual stresses after the previous processing due to slight changes in the shape of grain;
- Annealing - provides re-crystallization;
- Austenization - changes not only the form of grain, as with re-crystallization, but also changes the order of arrangement of atoms within the crystal lattice (austenite), which provides a better distribution of chemical elements within the grain.

**Holding at temperature** is required depending on the type of steel so that the whole part could convert its structure. The heating time should be determined based on the thickness of part.

**Cooling** largely determines the structure and quality of the steel. For some steels the cooling rate can change the structure and drastically change the metal properties without changing the chemical composition. An example is the hardening of steel 22MnB5, which due to the high cooling rate in water can provide a TS = 1590 MPa, and after annealing a TS = 480 MPa. Increased strength during hardening, of course, is a positive quality of steel, but keep in mind that the strength increases due to reduction of plasticity. Therefore, special attention should be paid to the processing temperature range of these steels. If during steel processing, the material is quenched involuntarily (for example, during a brief stop of the rolling mill), then further plastic deformation in addition to increasing the required force would lead to microcracks (**1, Fig. 12**).

In addition, the regimes of heat treatment affect the quality of the surface. It is related to the formation of cinder (**2, Fig. 12**) at high temperatures and overheating of the surface, which can lead to local melting (**3, Fig. 12**) and rippled surface (**4, Fig. 12**). Any deviation from the treatment regime leads to thermal cracking (**5, Fig. 12**). A use of protective atmosphere, which contains no oxygen, is only one way that can be used in order to prevent the formation of scale during the heat treatment.

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**Fig. 5 Examples of defects of heat treatment of steel**

1 – microcracks; 2 – traces of cinder; 3 – the local melting; 4 – rippled surface; 5 – thermal cracks
3.4. Welding, machining, final forming

As mentioned above, the operations of welding, machining and cold forming also influence the metal quality through chemical composition, strain and temperature. Therefore, we will discuss in detail the potential technology deviations and resulting product defects.

**Welding.** Liquid metal appears in the welding bath, and this metal at crystallization has to repeat the whole process of the base metal (discussed above). If this doesn’t happen, the area of welding and area around it are considered potentially affected (Heat Affected Zone). Modern welding technology can minimize this risk. However, the sparks falling on the surface of the finished product can break the metal structure (1, Fig. 13). In addition, the development of intergranular corrosion is typical for some stainless steels (2, Figure 13) at some distance from the weld. This is due to the formation of chromium carbides at certain temperatures, which are not only soluble in an aggressive environment, but also produce electrochemical corrosion.

![Fig. 6 Examples of factors affecting the welding](image)

1 – welding sparks;
2 – intergranular corrosion of stainless steels

**Mechanical treatment** may have a negative impact on the metal quality by increasing the temperature and (or) pressure. Typical features of this are heat tints and coarse scratches on the metal surface. Heat tints indicate that the thermal processing regime was not followed and there is a potential of local changes in the metal properties. Coarse scratches affect the appearance, as well as contribute to the development of corrosion.

**Final forming** operations can take place both in hot and cold state. Since operations are usually derived from a controlled technology, the deformations have small values. However, a large number of industrial claims are connected with errors at forming. For example - the failure in forming of a specified profile, associated with high yield strength. Another example - the appearance of microcracks during bending of the plate associated with the unevenness of deformation in middle layers and surface of the sheet.
In conclusion we provide two additional examples that illustrate the impact of technology product quality.

1. Effect of deformation on the properties of cold-deformed stainless steel tube and the quality of its surface (Fig. 14)

![Fig. 7 Effect of deformation on the properties of the metal and the quality of its surface](image)

This example shows that the local non-uniformity of the properties can lead to deterioration of the quality and corrosion resistance of the entire finished pipe. This kind of defect isn’t reason for rejection under the standard contractual requirements. Standard mechanical properties tests do not reveal the local hardening. A specimen for corrosion test can be cut out from a non-hardened tube section. Non-destructive testing in this case is useless, since it reveals the actual defects, rather than the potential ones.

2. The influence of small notches on the corrosion resistance. Cold deformed tubes or products that have been mechanically processed may have small notches or roughness on the surface. With the help of standard characteristics of roughness $R_a$ and $R_z$ is almost impossible to distinguish two fundamentally different types of scratches: with gently sloping and sharp edges. The second type of scratch is dangerous as a stress concentrator and a reason of stress corrosion (Fig. 15).

![Fig. 85 The influence of scratches with sharp edges on the metal surface on the development of stress corrosion](image)
Stretches on the surface of metal parts are positioned in different directions. They are parallel to the direction of rolling or mechanical processing and perpendicular to the direction of bending. During quality control of the surface, movement of the scanning device perpendicular to the scratches is important. For example, the usual practice of measuring the depth and shape of scratches on the surface of the pipes is parallel to the axis, while the stretches are also parallel to this axis. More useful in this case is the quality control in a circumferential direction.

Previous brief description of the metallurgical technology has allowed us to identify such potentially dangerous aspects that may be not listed in the standards, but have an impact on product quality:

- The distribution of chemical composition in the grain of the metal.
- The distribution of chemical composition over thickness of the product.
- The distribution of grain shape and size over the product.
- The phase composition of the metal and its distribution over the thickness of the metal.
- The position of the actual properties of the metal in the allowed values.
- Yield strength (in many standards not specified).
- The thermal regime of the deformation.
- The degree and distribution of deformation.
- The mode of heat treatment and its consistency with the thickness of the product.
- Residual stresses.
- Obvious and hidden defects.
- The quality of surface and shape of roughness.

Accordingly, the objective of quality monitoring is to determine the control points, control methods and combinations of tests to detect these potentially dangerous aspects.
4. **Criteria for evaluating the quality and control methods**

In modern facilities, quality control is ensured by quality assurance. A document that includes a description of the product quality process when passing through multiple manufacturing operations (i.e. traveler or manufacturing card- Traveler or manufacturing card is the main document that indicates manufacturing and control operations to be performed in the workshop. It represents the manufacturing history of each part) is included with the material as it is processed. Usually, the quality control results are entered in it directly during the process. In this case, it is non-destructive control methods, which can be integrated into the process: chemical composition, sizes, visual inspection of defects, UT (ultrasonic testing) and ECT (eddy-current testing), etc. Laboratory quality control is performed with specimens that are cut from the product towards the final stop (product complete). Results of control shall be reported later to the buyer. The volume of data is also determined by the contract terms. The chemical composition, size, the results of nondestructive testing and the results of laboratory tests are usually entered in the certificate.

Results of laboratory tests are, in fact, integrated characteristics of quality indicators of each technological stage, presented in **Table 1**, and described above. The data contained in a traveler card or manufacturing card is usually not disclosed to the buyer. Thus, the analysis of traveler or manufacturing card is an additional way to control production process. For example, the number of turns and passes in the rolling mill indirectly determines the degree of structure workup and anisotropy of properties, but this indicator is usually not passed on to the buyer. Consequently, we can distinguish two groups of quality criteria:

- Technological (based on the monitoring of equipment and technology);
- Physical (determined by the results of measurements and tests).

Thus, the following manufacturing operations (**Table 3**) should be considered in terms of these two criteria.

In **Table 3**, the position of the total line "laboratory tests" should be noted. Here it is situated at the end of the table, which is logical, since the results of laboratory tests are the integral characteristics of quality indicators achieved in all previous operations. However, in reality, these tests are not always carried out at the completion.
Table 3
Check points and quality criteria in the technological process

<table>
<thead>
<tr>
<th>Technology</th>
<th>Check point</th>
<th>Technological criteria</th>
<th>Physical criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Steel Mill &amp; Part development</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>1.1 Processing Iron &amp; Scrap metal into Steel</strong></td>
<td>In liquid metal In furnace In ladle</td>
<td>The presence of aggregates of out-of-furnace treatment, electroslag remelting, AOD, etc. The volume of melting. Temperature regime and processing time.</td>
<td>Chemical composition</td>
</tr>
<tr>
<td><strong>1.2 Casting: Ingot or Continuous</strong></td>
<td>In process</td>
<td>Type of process (here it should be kept in mind what steel grades were involved. For example, continuous casting is not suitable for rimmed steels). The presence of electromagnetic stirring. temperature regime and crystallization rate.</td>
<td>Chemical composition, homogeneity of chemical composition</td>
</tr>
<tr>
<td><strong>1.3 Forging</strong></td>
<td>In process</td>
<td>Size, temperature, number of passes and turns, the way of feeding of ingot (for ingots), strain; total and along the sides, the shape and design of tool, rolling force, and other technological elements</td>
<td></td>
</tr>
<tr>
<td><strong>1.4 Finishing Process</strong></td>
<td>In process</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>1.5 Forging &amp; Rolling of processed steel</strong></td>
<td>In the end</td>
<td>The shape and size of product, defects, mechanical properties, metal structure homogeneity, stresses, quality of the surface, isotropy of properties</td>
<td></td>
</tr>
<tr>
<td><strong>1.6 Heating (Thermal treatment)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>1.6.1 Heating</strong></td>
<td>In process</td>
<td>Methods of heating and cooling. Temperature. The presence of a protective atmosphere. The rate and method of heating and cooling. Exposure time.</td>
<td>The structure, size and shape of the grains, mechanical properties, distribution of properties of product by thickness, the internal stresses, defects.</td>
</tr>
<tr>
<td><strong>1.6.2 Cooling</strong></td>
<td>In the end</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technology</td>
<td>Check point</td>
<td>Technological criteria</td>
<td>Physical criteria</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>-------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>1.7 Finishing, Tracing &amp; cutting</td>
<td>In process</td>
<td>Types of operations. Temperature. It is important that the local heating or deformation does not lead to breach of the achieved properties. For example, the appearance of heat tints during grinding or local hardening during straightening. The quality of the surface. Dimensions.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>In the end</td>
<td></td>
<td>Surface quality, sizes, precision, and properties on the surface, such as hardness.</td>
</tr>
<tr>
<td>1.8 Form Parts</td>
<td>In process</td>
<td>Types of operations, temperature, deformation parameters, the quality of the tool, friction.</td>
<td>Sizes, shape, surface defects, distribution of mechanical properties.</td>
</tr>
<tr>
<td></td>
<td>In the end</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Σ Laboratory tests</td>
<td>In process</td>
<td>Characteristic of test, for example, method of determining the corrosion resistance. The number and location of specimens. The orientation of specimens relatively to the current factors, such as force at the test. The orientation of specimens relative to the direction of the treatment history, for example, rolling. The quality of the tests.</td>
<td>Non-destructive testing of product (UT, ECT, pressure tests, such as hydraulic, etc.); Tests aimed at measurement of strength and plasticity (compression, tension); Tests aimed at prediction of behavior of product (long-term and fatigue strength, torsion, bending, dispensing, flattening, hydraulic, control of residual stresses, etc.); Tests of metal products (chemical composition analysis, metallography, hardness, corrosion resistance, magnetic test, etc.).</td>
</tr>
<tr>
<td></td>
<td>In the end</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Similar tables may be presented for other technological processes.
5. **Particular recommendations for ship building and the offshore industry**

The following harmful environmental influences are characterized for metal products used in ship building and the offshore industry:

- corrosion activity;
- loads that are variable in strength and direction;
- large temperature range;
- long lifetime.

Therefore, in accordance with the above factors, it is necessary to conduct the following laboratory tests (Table 4):

**Table 4**

**Recommended laboratory tests**

<table>
<thead>
<tr>
<th>#</th>
<th>Type of test</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Corrosion resistance</td>
<td>This test should be conducted not only for the material, but also for the finished product. For example, the notches and cracks that occur at bending of the sheet can reduce corrosion resistance. For responsible products is desirable to carry out full-scale tests: 1. power load that is similar to working conditions; 2. exposure to the atmosphere that is similar to working; 3. corrosion tests; 4. mechanical and (or) technological tests;</td>
</tr>
<tr>
<td>2</td>
<td>Fatigue strength</td>
<td>The test should be also conducted with specimens that are cut from the surface layers of the metal where may exist significant tensile residual stresses</td>
</tr>
<tr>
<td>3</td>
<td>Cycle tests</td>
<td>The specific form of tests should be selected on the basis of the working conditions of the finished product</td>
</tr>
<tr>
<td>4</td>
<td>Metallographic study</td>
<td>Specimens should be cut from the surface and central layers of the product</td>
</tr>
<tr>
<td>5</td>
<td>Nondestructive testing</td>
<td>It is important to carry it as close as possible to the end of the technology. For example, to detect surface defects (notches and cracks) those appear at incorrect bending mode</td>
</tr>
<tr>
<td>6</td>
<td>Hardness</td>
<td>It is important not only the average value, but also the distribution of values by volume of product’s body</td>
</tr>
<tr>
<td>7</td>
<td>Tensile tests and impact tests</td>
<td>It is important to choose the direction of force</td>
</tr>
<tr>
<td>8</td>
<td>Bending test/folding test</td>
<td>As close as possible to real conditions of sheet metal behavior at forming (for example, hull)</td>
</tr>
<tr>
<td>9</td>
<td>Special tests</td>
<td>Hydro-testing, physical testing to ensure the customer requirements</td>
</tr>
</tbody>
</table>

This list of tests is not complete and depends on the product and the requirements applied to it.
6. **Features of quality control for some types of products**

a. Sheet products. In most cases, a metal sheet is a work piece for forming a product of more complex shape. Therefore, during evaluation of the sheet quality the following points should be additionally taken into account: 3D (for a thin sheet - 2D) orientation of the specimens for testing; control of structure uniformity and properties in size and thickness, not too high values of yield strength, quality control of the surface, carrying out technological tests simulating the conditions for further processing.

b. Bar and rod products. Most dangerous is the preservation of casting (ingot) defects: shrink hole, axial porosity and other defects of the liquid metallurgy. Traces of these defects may occur even in a 5mm diameter rod. Moreover, these defects in accordance with the elongation factor are distributed for miles, making the material unfit for use. It is possible to control by using non-destructive methods, as well as thorough monitoring.

c. Rolled profiles and Web Joist. Important here is the control of the flange properties and the wall profile, the control edges of the profile; the control surface properties and the corners and curves. The inner side is susceptible to folds and notches, and the outer to cracks.

d. Tubular products. For tubes and pipes the structure uniformity and properties of length, wall thickness and perimeter are important factors. Therefore, the tests must be performed in the longitudinal, radial and tangential direction. It should be noted that the quantitative methods of evaluation of tube properties in the radial and tangential directions today are poorly developed. The evaluation criterion in this case is the appearance of visible signs of destruction, and in their absence the tube is considered acceptable. This situation does not allow quantifying the plastic properties of metal to determine the tube quality. The technology should control the ratio of reducing of diameter and wall thickness, also the number of rolling cycles. An important criterion is the type of technological process of billet piercing: piercing press, helical rolling mills, drilling. The type of the piercing affects the metal properties: the press piercing is affecting the difference in grain size of the wall thickness, and the piercing on the helical rolling mills - the issues of the inner surface. It is also desirable that the technology has minimized the expansion of hole. For quality control of the surface particular attention should be paid to the inner surface, because there it is probable to find the notches, blisters or scabs.

e. Welded products. It is important to control the difference between the structure and properties of the weld metal and base metal, absence of fusion lacks, and also for high-alloy steels - intergranular corrosion.
7. **Conclusion**

For improving the quality and reliability of metal products, the client should:

1. Conduct regular technical audits of the manufacturer by reviewing the technical capabilities and related documents in order to determine the accuracy of technical procedures within the field of tolerances.

2. For certain cases, develop and implement their own form of traveler or manufacturing cards which can include information about significant or potential production risks at any stage of the process.

3. Use methods and laboratory tests from (Table 4) more widely. For this the client will have to provide reference values for the measured rates.

4. Introduce the practice of metallographic analysis of potentially affected products and problem areas, including a method of investigation of defects causes.

5. Establish original check points for product quality control in accordance with the technological process and potential failure modes. For example, control of the metal structure immediately after rolling or forging.

6. Choose areas for sampling and directions of the tests in accordance with future product processing and history of its pre-treatment.

7. Create a database and determine the empirical dependencies between quality indicators and the modes of treatment.