Sucker Rod Design-Steel Mill to Oil Well

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After consideration of all component parts in a sucker rod pumping installation, it is believed that the sucker rod string most directly affects the action and performance of the entire system. Sucker rod behavior, in transferring the forces and loads that are involved, determines the action of the subsurface pump. The load imposed on the surface equipment are attributed directly to the inherent characteristics of the sucker rods. The allowable stresses, range of loads imposed and speed of operation, which a sucker rod string can withstand without excessively frequent breakage, limit the economic depth and capacity of an installation.

Studies of the behavior of sucker rods and improvements in their metallurgical properties have contributed toward an increase of economic life of sucker rod strings. It is believed that an understanding of the overall design, from steel mill to well bore, would be beneficial to the person charged with the operation of sucker rod pumping installations.

There are many variables that must be considered before the trained field personnel can make the proper selection of a sucker rod string. Each well presents individual problems, and a close analysis of anticipated conditions is essential in making this proper selection. Depth, volume, and corrosion are the three primary factors.

In the manufacture of a sucker rod, all of these variables must be combined in order to have available a few grades of rods to handle all known conditions. It is the problem of the metallurgist to select the proper material, which will produce a sucker rod to perform satisfactorily under these conditions.

A few of the materials and their characteristics available to aid the metallurgist in his solution of the problem are as follows:

1. Carbon
   Pure iron is very ductile and has relatively low strength. The addition of small amounts of carbon will increase the strength, but in turn decrease ductility. Low carbon or mild steels cannot be heat treated to the desired strength level. Medium carbon steels are characterized by higher tensile strength and hardness with resulting decrease in ductility and impact resistance. They show a definite change of mechanical properties when heat treated.

2. Manganese
   All commercial steels contain varying quantities of manganese as an alloying element to produce higher strength and greater response to heat treatment. Small amounts of manganese present in steels act as a deoxidizer and cleanse the melt of foreign matter.

3. Silicon
   Silicon is one of the principle deoxidizers or cleansers used in the refining of steel. When used in percentages above that normally required for deoxidation, silicon can improve oxidation resistance and strengthen low alloy steels.

4. Chromium
   Chromium is used to increase strength and corrosion resistant properties. Nickel-chromium alloy steels are excellent for many purposes and in some cases better than straight chromium steels.

5. Nickel
   Nickel when present in appreciable amounts provides increased strength, hardness, and impact strength. It is used as an alloying agent in sucker rods where corrosion is a factor. It helps protect steel from embrittlement and pitting caused by Hydrogen Sulphide fluids.

6. Molybdenum
   Molybdenum has a great effect on the hardenability of an alloy steel, and also increases corrosion resistance and toughness.

7. Vanadium
   Vanadium is used to refine the grain structure and improve the mechanical property balance. It also increases the effect of primary alloying agents.

8. Copper
   Copper is added to increase the corrosion resistance in the sucker rod.

9. Boron
   Boron is used as a strengthening agent by increasing the hardenability of the steel.

After the metallurgist has chosen the type steel, it is ordered from the mill with very exacting specifications. These specifications include close diameter and length tolerances, special surface conditions, fine grain structure, and straightness.

Quality control is introduced at the mill right at the start in the selection of raw materials. Carefully weighed charges of iron ore, coke, and limestone form alternate layers in the blast furnace, resulting in the end product of pig iron. The pig iron is then charged into an open hearth or electric furnace. Again carefully measured charges of slagging material and scrap are added to the melt. After the proper refining cycle, the melt it brought to the desired carbon and alloy content by suitable additives.

After all disolved oxygen is removed by the addition of Ferro-Silicon, a final chemical analysis is made to be certain that the correct chemical composition has been obtained.

Each heat of steel is then tapped into ladles from which it is poured into molds to form ingots. The mold is stripped from the ingot after sufficient solidification. The ingot is then placed in a soaking pit to insure homogeneity and to reach a uniform temperature for rolling, free from any chemical segregation.

A billet is formed from the ingot by successive passes through the Blooming Mill. This hot working not only reduces the ingot to a workable size, but also improves the properties of the steel. The coarse crystalline structure of the ingot is replaced by a fine grain structure. Inspection for surface defects are made at this time.

Successive rolling and shaping operations gradually reduce the cross-section of the reheated billet until a rod the size and shape of a sucker rod is achieved. All dimensions are closely checked to assure desired size.

The metallurgist then takes samples from these finished raw material rods and heat treats them to obtain desired mechanical properties. The results obtained from these pilot samples determine the time and temperature of heat treatment that will produce the best combination of mechanical properties. They are also tested for chemical composition and grain structure.

The first stage in the manufacture of the sucker rods is the straightening process. Even though the bars are rigidly examined at the mill for straightness, this process is included to provide a rod that is perfectly straight, true, and free from kinks or bends.

The next step is to forge the upset of the rod, and this requires heating the steel until it reaches a plastic state. A close control of temperatures and length of time to bring the steel to forging temperature is quite important. This assures maximum strength and ductility in the forging by providing streamlined flow lines of metal and freedom of flooding and overlapping. At each of six stages during the forging operation, the rod is in a die that causes the steel to plastically flow under compression, resulting in refined grain structure and high strength properties. During the forging operation, the wrench flat is forged such that it is concentric with the body of the rod.

The sucker rod is then ready for the heat treatment stage. Until recent years all sucker rods were merely normalized on each end to reduce some of the stresses that resulted from upsetting. It is now the accepted practice to full length normalize sucker rods. The term "normalize" is defined as "heating iron base alloys to approximately 100 F above the critical temperature range, holding above that range for a proper period of time, followed by cooling to below that range in still air at ordinary temperature". Normalizing imparts to the rod the desired combination of strength, ductility, and impact resistance. It relieves internal stresses by homogenizing and equalizing grain structure throughout the steel. The temperature and time involved in this process are decided from the pilot samples previously tested.

Most alloy steel sucker rods are also drawn in addition to the normalizing process. This insures balanced physical structures and a stress-free internal structure. Plain carbon rods are not drawn because of the relatively stress-free structure resulting from normalizing alone.

During the heat treatment the rods travel through the furnace and a rolling action is imparted to the rods. The rolling action of the rod insures perfect straightness and uniform temperature.

The high temperatures during the heat treatment operations cause the sucker rods to become incased with a thin coating of iron oxide. This scale must be removed to prevent galvanic corrosion and to prepare the surface for painting. The rods are subjected to a blasting action of thousands of small round steel shots.

After the surface has been cleaned, the pin and shoulder of the rod must be machined. To insure concentricity, the rods are chucked in automatic lathes on the wrench flat. Special operations were performed during forging to make the wrench flat concentric with the body of the rod. Therefore, by chucking on the wrench flat the pin is machined concentric, and the shoulder face perpendicular, to the longitudinal axis.

"Go" and "No Go" gauges are used to check the conformity of the pin and shoulder to API standards. At this stage couplings and thread protectors are placed on the rod.

The rod string is only as strong as its weakest link. Therefore, it is imperative that the same care be taken in the manufacture of the rod couplings. These couplings are made from a material that can be given a uniform hard exterior case and retain strength and ductility on the threaded area. The exterior surface must be ground to a fine finish to eliminate stress concentrations in the hard case. The faces are ground perpendicular to the longitudinal axis to mate properly with the sucker rod shoulder. Every coupling is then thoroughly inspected to insure conformity with API standards.

The couplings are then secured on the rod by means of an air wrench, which provides ample torque to stress the pin to a pre-determined value. The correct value for torque required is difficult to ascertain because of the unknown frictional coefficients existing between rod pin shoulder and coupling face. However, it can be stated that the pin should be stressed to a value greater than the maximum operating stress. This will eliminate the possibility of separation of the two faces and imposition of a bending moment. The following values for torque and force with a 3' lever arm are suggested:

SIZE	TORQUE	FORCE WITH 3-in. CHEATER
Rod	Ft-lbs.	Lbs.
5/8"	215	72
3/4"	340	113
7/8"	515	172
1"	775	258

The rods are then painted with a protective coating and dried with small heating elements. This coating should remain on the rod and should not slough from the rod while in the well.

A good sucker rod design is one that will transmit maximum power over an indefinite period with the minimum investment. The steel mills and rod manufacturers have made an end product that if properly field designed and used will transmit maximum power over extended periods.

A great number of sucker rod failures are attributed to over-stressed conditions and the mechanism of these failures is that of fatigue or corrosion fatigue. The deterioration and failure of metals caused by repetition of stresses is defined as fatigue. If pitting occurs because of corrosion attack, than fatigue is accelerated because of decreased cross-sectional area and stress concentrations at that point. The endurance limit or fatigue strength of a sucker rod is the highest stress the steel will withstand without failure after a specified large number of stress reversals, usually ten million. Because sucker rods are subjected to thousands of stress reversals each day, the endurance limit becomes important in the evaluation of expected sucker rod life. Important factors with which to be concerned in endurance limit are the maximum stress and minimum stress, or stress range, and the rapidity which these reversals occur. Therefore, it is clearly seen that by controlling to a certain extent the above factors, then the fatigue life of a sucker rod string is increased.

The phrase "under ideal pumping conditions" is often included in any discussion concerning the allowable maximum working stresses of sucker rods.

"Ideal pumping conditions" of course require definition and possibly may differ with certain people's viewpoints. It is the consensus of this writer that the major conditions to be of concern are:

1. Maximum operating stress.
2. Minimum operating stress.
3. Range of stresses from #1 and #2 - known as load range.
4. Pumping speeds that induce vibrational forces inherent in the rod string.
5. Extraneous forces caused by "pumped-off" conditions or gas interference.
6. Fluid conditions that would cause corrosion attack, embrittlement or interference to normal gravitational fall.

The above six factors are so closely related that each must be considered in handling the integral problem.

The maximum load or stress to be imposed upon any grade of rod is always a certain fractional percent of the minimum yield strength of that specific type sucker rod. Of course when stressed over the yield point, the rods take a permanent strain and remain distorted. This can occur in endeavoring to unseat a "stuck" pump. A rough rule of thumb is 50% of the minimum yield strength for a maximum operating stress.

It is impractical to consider the operation of a sucker rod installation at a zero minimum stress. This, of course, would place a number of rods at the bottom of the string in compression, causing buckling. Buckling imposes bending moments in the rod string creating additional stresses.

The difference of maximum load and minimum load is referred to as load range. It often is used in the form of a ratio, which then may be used to correlate information from other well operations. This is the ratio of actual load range to the maximum load.

$$\text{Load Ratio} = \frac{(\text{Maximum load} - \text{Minimum load}) \times 100}{\text{Maximum load}}$$

Good operation is to endeavor to keep the load ratio at a minimum value. Caution should be taken when ratios exceed 70%. As is evident from the formula, the only way to improve - decrease - the ratio is to either decrease the maximum load or increase the minimum load. It is quite difficult at times to decrease the maximum load and maintain the same rate of production. However, often times the minimum load can be increased without any material affect on the volume of fluid produced. Stroke length, speed, type pump and plunger fit, paraffin deposition, etc. are factors to be considered on load ratio.

Operating speed is one of the major factors which in turn influences greatly the other five that are listed. On the upstroke of the pump, the plunger picks up fluid and imposes a concentrated load at the bottom of the sucker rod string. The steel sucker rods, being an elastic-system, stretch because of this concentrated fluid load. This stretch stores energy in the rod string. On the downstroke, the rod load is released and transferred to the tubing string. This storing and releasing of energy induces vibration in the rod string. The timing of these forces may tend to increase the vibration and produce excessive stresses in the rods, causing premature failures. This occurs at synchronous speeds. The timing, however, may be chosen as to diminish the vibrations and completely cancel them out at each half stroke. This, of course, is a non-synchronous speed.

Also the fall of sucker rods can be no greater than that afforded by the natural acceleration of gravity. Any frictional forces in stuffing box, tubing deposition, low gravity fluid, crooked hole conditions, and sub-surface pump retards the free fall. The maximum is considered to be approximately 4,000 inches per minute of average polished rod velocity.

Extraneous forces either add impact loading or increase the frictional load to the system. A fluid pound, liquid or gas, caused by insufficient fill of the pump's displacement chamber creates additional loading on the rod string. This not only creates an impact load, but also places the lower extremity of the rods in compression, causing buckling and a bending moment. Frictional forces in stuffing boxes, paraffin deposition, low gravity fluids, and pumps increase maximum or peak load and decrease minimum load. These should be controlled if at all possible.

The condition of fluid being produced often becomes one of the major factors. A corrosive fluid that causes localized pitting not only decreases the cross-sectional area of the rod, but causes a stress concentration at that specific point. Embrittlement of steel from a hydrogen-sulphide fluid reduces ductility in the rod and materially decreases the endurance limit. Generally speaking, embrittlement and corrosion occur simultaneously in hydrogen-sulphide fluids.

The production of low gravity fluid creates a problem in that the natural fall of the rod string is retarded because of the viscuous nature of the fluid. Heavy and rigid rod strings, dilution, loose fit pumps and bottom hole heaters all aid in this problem.

Sucker rod pumping and the problems involved are often considered a very simple operation. Unfortunately, this is an illusion, as these problems become quite complex because of the many variable conditions found in oil wells. Even with these difficult and complex problems, it is the most efficient and satisfactory artificial lift method yet developed when such production falls within the limits of sucker rods.