SOME METALLURGICAL CONSIDERATIONS IN CENTRIFUGAL COMPRESSORS

by

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INTRODUCTION

Consideration of the materials for use in rotating machinery must begin with careful study and appraisal of expected operating conditions. In the discussion which follows, attention is concentrated on centrifugal compressors, but similar considerations are required in other types of turbomachinery such as axial compressors and steam and gas turbines. In addition to the nominal conditions of operation, it is also necessary to take into account expected variations in these conditions. It is necessary to know whether variations are expected to be transient, or of long duration. Sometimes, machinery is purchased for intermittent operation, and this is usually the most severe kind of service.

Environmental factors which must be considered include:

1. The operating stresses of rotating parts are determined by the design, size, and speed of rotation, and these stresses must be known for the obvious reason of avoiding selection of materials having insufficient strength.

2. With regard to the casing and other stationary machine elements, the operating stress must also be known, and for these parts, the stress is determined primarily by size, design, and internal pressure.

3. The gas which is to be handled by the compressor must be evaluated for aggressiveness with respect to the materials of construction. If high corrosion rates are expected with ordinary materials, alternate materials must be selected, even though substantial additional cost may be incurred.

4. The expected temperature of operation must be determined. Temperature is a factor in all of the above three items. It affects the rate at which corrosion reactions proceed, affects the strength of material, and determines susceptibility to brittle failure.

PROPERTIES WHICH REQUIRE CONSIDERATION

Virtually all of the properties of materials must be considered in evaluating materials for use in centrifugal compressors. A list of the properties includes:

1. Tensile properties at room temperature and actual operating temperature.
2. Modulus of elasticity.
3. Coefficient of thermal expansion.
4. Susceptibility to brittle failure (toughness).
5. Damping.
6. Fatigue strength.
7. Thermal conductivity.
8. Specific heat.
9. Hardenability.
10. Weldability.
11. Corrosion resistance.

Not all of these properties are important in every application, but various combinations of required properties must be evaluated depending on service requirements in each instance. A notable omission from the above list is long time high temperature properties such as creep or stress rupture. Only infrequently do centrifugal compressors operate at temperatures high enough to require consideration of these properties. They are much more commonly considered in turbines.

problem is encountered in meeting the requirements at temperatures down to −50°F using carbon steel filler metal for either manual metal arc or submerged arc welding. For temperatures below −50°F alloy steel filler metal is required and special fluxes are needed for submerged arc welding. These are available. Representative data are shown in Tables 5 and 6 for tests on weld metal and heat affected zones respectively.

Fluxcore welding with products designated by the American Welding Society as E70T-X is attractive for use at ordinary temperatures because the deposition rate is higher than that of manual metal arc, and the technique may be used in positions where submerged arc welding is not applicable. Satisfactory low temperature impact results have not yet been obtained on fluxcore deposits consistently, but development along these lines is continuing.

Cast materials for casings are also available for service to −175°F using one of several low alloy nickel containing steels with 2¼% nickel being satisfactory to −100°F, 3½% nickel to −150°F, and 4½% nickel to −175°F. Below −175°F materials must be used which have an austenitic structure. Down to at least −320°F conventional cast austenitic stainless steels such as the cast equivalent to AISI Type 304 possess good fracture toughness. A modified 20% nickel cast iron has also been used for application at −260°F, and toughness values indicate that it would be acceptable to −320°F. While Type 304 is more difficult to cast, and more expensive, it also can be welded more readily. In conventional austenitic stainless steels such as Type 304,

TABLE 5. WELD METAL IMPACT STRENGTH

Weld Metal	Method	Temp. °F	Impact Energy Ft.Lbs. Average	Lateral Expansion Mils Average
E7018	Manual	−50	51	46
L61-860[1]	Sub Arc	−50	23	21
E8018-C1	Manual	−75	42	34
L61-AXXX19S[1]	Sub Arc	−75	53	46
Cryoweld 3[2]	Manual	−150	31	24
XW-19[3] & 709-5[4]	Sub Arc	−150	18	11

[1]Lincoln Electric Company
[2]Champion Commercial Industries
[3]Armco Steel Corporation
[4]Linde Division, Union Carbide Corporation

NOTE: In submerged arc welds, first grouping refers to wire designation whereas second refers to flux.

TABLE 6. HEAT AFFECTED ZONE IMPACT STRENGTH

Base Metal	Method	Temp. °F	Heat Affected Zone Impact Energy Ft.Lbs. Average	Heat Affected Zone Lateral Expansion Mils Average
A516 Grade 55	Manual	−50	119	79
A516 Grade 55	Sub Arc	−50	49	45
A203 Grade A	Manual	−75	43	34
A203 Grade A	Sub Arc	−75	53	44
A352 Grade LC3	Manual	−150	23	18

the weldability is good and the properties of the base metal, heat affected zone, and weld metal are all good at low temperatures. The modified 20% nickel cast iron has better foundry properties and requires fewer welds. There is more of a problem, however, with welding, and especially with the heat affected zone of the base metal. For this reason welds in critical areas are not permitted, but non-critical locations are sometimes repaired.

In both materials, because of the austenitic structure, the coefficient of thermal expansion is about 50% greater than that of standard ferritic casings. This is not an insurmountable problem, but it must be taken into account, especially if the rotor is constructed of a material with a lower coefficient of expansion. Rotors for operation at −260°F have been fabricated from 9% nickel steel. This alloy has satisfactory resistance to brittle failure at least as low as −320°F. Its coefficient of expansion is similar to that of the low alloy steels, and thus much lower than that of austenitic casings. In the form of forgings and plates up to about two or three inches in thickness the alloy has attractive properties, but it is not available in the heavier thicknesses required for casing flanges. Castings of 9% nickel steel are not used because, while they can be made, they do not have attractive properties.

Materials for Rotating Parts

Extensive work at the Naval Research Laboratory by Pellini and associates showed that the energy absorption requirement for the prevention of brittle failure increased with the strength of the material. While a level of 12 or 15 ft.lbs. in the Charpy V notch test is sufficient for ordinary mild steel, the energy absorption requirement might be 30 ft.lbs. or more for quenched and tempered low alloy steel (26). Recognizing this problem, Gross and associates at Lehigh (27) and at U. S. Steel (28) proposed a criterion using a direct measure of notch ductility. They examined both the lateral contraction at the root of the notch and the lateral expansion on the compression side opposite the notch. They concluded that either would serve, but that lateral expansion was a great deal easier to measure than lateral contraction, and for this reason, expansion was selected. Gross et al proposed a criterion of 15 mils lateral expansion for a wide range of strength levels. This has since been incorporated in the ASME Boiler and Pressure Vessel Code, Section 8, Division 1 for materials having a tensile strength greater than 95,000 psi. There is, however, still some difference of opinion on this subject as indicated in a recent paper by Puzak and Lange (29) of the Naval Research Laboratory. The Naval Research Laboratory work shows a superiority for other types of tests, especially the drop weight and drop weight tear tests. Unfortunately these tests require test specimens which are difficult or impractical to obtain from some forms of material.

In the case of rotating elements, AISI 4330 or 4340 can be heat treated to give acceptable values using lateral expansion, per ASME Boiler and Pressure Vessel Code, Section 8, Division 1, down to temperatures at least as low as −150°F with a yield strength of 90,000 psi or greater. At −100°F, the same impact test requirement can be met with a yield strength of about 105,000 psi.

Some years ago 3½% nickel steels such as AISI 2340 were used for this application. More recently AISI associated with the lesser fracture toughness of higher strength steels, and with the increased stress gradient at the base of a notch or crack in higher strength materials.

The relationship between the stress at operating speed and that during factory overspeed testing has been reviewed earlier. As in the case with sulfide cracking, this relationship provides a margin of safety in hyrogen environment embrittlement. During overspeed testing there may be plastic deformation and some blunting of stress concentrations. Such testing is commonly carried out in a partial vacuum. Subsequently, operation at a lower stress in a more severe environment is then less hazardous.

LOW TEMPERATURE OPERATION—BRITTLE FAILURE

Background

When compressors are required to operate at sub-zero temperatures, consideration must be given to the problem of brittle failure. As temperatures fall, all materials become stronger and less ductile, and some materials become increasingly susceptible to brittle failures. Those materials which have this susceptibility include most of the materials commonly employed in compressor construction. In order for a brittle failure to be initiated, there must be a stress exceeding the yield strength. While the nominal stress is always well below the yield strength, it is not possible to design and manufacture any engineering structure without stress concentrations, and it is from these sites that brittle failures propagate. Brittle failures, once initiated, can propagate at very much lower stresses. Such failures propagate with the speed of sound, and this is the reason for reports of a loud noise accompanying brittle failures, such as those which occurred when welded ships broke in half during World War II. The problem, of course, was not with the welding, but it had not been encountered previously because brittle failures in individual ship plates frequently did not propagate across riveted joints. Individual plates were replaced when they cracked. In the case of welded ships, however, the path for propagation across the joint existed, and catastrophic failures were encountered.

Criteria for Resistance to Brittle Fracture

There have been several changes in the criteria for susceptibility to brittle failure. In the work done immediately after World War II, the most commonly accepted criterion was the Charpy V notch impact tests using energy absorption to determine susceptibility. It gradually came to be realized that the previously used Charpy keyhole test was not as definitive as would be desired for the reasons shown in Figure 11. It may be seen that in the transition zone there is a spread in the Charpy keyhole values where the energy level obtained is unpredictable while the Charpy V notch test is more definitive. For this reason the Charpy keyhole test was superseded by the V notch test, still using energy absorption as a criterion.

Other tests have been used including the explosion bulge test, the drop weight test, and the drop weight tear test. These tests have the advantage of being more direct measurements of the susceptibility to brittle failure. They suffer, however, from the disadvantage of having associated with them one or more of such problems as requiring large size test specimens, expensive test setups, test specimens not readily obtainable from some forms of material, etc.

The ultimate in criteria for resistance to brittle fracture seems to be fracture mechanics. A great deal of work has been done in this area over the last twelve or fifteen years, particularly with respect to ultra-high strength materials and certain non-ferrous alloys such as aluminum and titanium. At the present state of development, fracture mechanics is not fully applicable for the low alloy steels at the strength levels and the temperature levels commonly encountered in centrifugal compressors. The fracture mechanics approach is the best one for taking fully into account the fact that flaws exist in all materials and all structures. There is a finite size below which flaws will not propagate. The actual size is dependent on the strength of the material and the applied stress. It seems probable that ultimately fracture mechanics criteria will be developed, and will replace measurements presently in use.

Materials and Fabricating Procedures

Casing materials for low temperature service generally require only modest strength, and there are several grades of both wrought and cast products.

For fabricated casing material, fine grain carbon steels are available with satisfactory properties at temperatures to −50°F, 2¼% nickel steel plates will go to −75°F, and 3½% nickel steel plates may be purchased for service to −150°F. In the case of the 3½% nickel steel at −150°F, ordinary melting procedures are not capable of yielding satisfactory results in thicknesses over about four inches, but considerably improved results are obtained with electroslag melted material. The improvement is believed to be due to the substantially lower level of impurities. The properties of these materials at low temperatures are sometimes enhanced by accelerated cooling after the austenitizing treatment. This is particularly helpful in heavier thicknesses, say over three or four inches.

In order to take advantage of these materials, it has been necessary to develop fabricating techniques including, most especially, welding procedures. No great

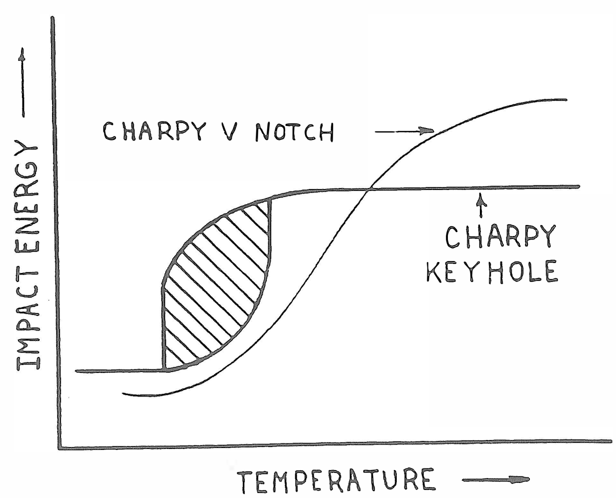

Figure 11. Charpy Keyhole and V Notch Impact Energy as a Function of Temperature.

and in air with no reduction in strength or ductility due to hydrogen environment embrittlement. Surface cracking is not observed.

Effect of Variables

As has been indicated, the effects of variables on hydrogen environment embrittlement have not been as fully defined as is desirable, presumably due to the extreme difficulty and cost of the experimentation.

Hofmann and Rauls (24) have reported on the effect of temperature. In their work, embrittlement seemed to be most extreme near room temperature, decreasing as the temperature was raised or lowered. This work was on normalized low carbon steel. As shown in Table 4, other studies (21) on AISI 4140 quenched and tempered to two different strength levels showed the same degree of embrittlement at 80°F and 250°F. The higher strength material, having a yield strength of 212,000 psi, exhibited a greater degree of embrittlement than other specimens with a yield strength of 127,000 psi.

Elastic properties, including the yield strength of a material, are the same in hydrogen as in air. Some plastic deformation is required to initiate hydrogen environment embrittlement. For this reason it has been observed that low alloy steels quenched and tempered to produce a tempered martensite structure are less prone to embrittlement in a hydrogen atmosphere than lower strength materials. In a tempered martensite structure, the ratio of yield strength to tensile strength is usually 0.85 or higher, while in lower strength materilas the yield-tensile ratio may be as low as 0.5 because of the difference in heat treatment. Thus, deformation begins at a lower fraction of the tensile strength in the lower strength materials with the result that a greater depression in tensile strength due to hydrogen environment embrittlement is observed.

TABLE 4. DEPENDENCE OF FAILURE ON MATERIAL YIELD STRENGTH IN HYDROGEN AND NITROGEN ATMOSPHERE

		Stress-rupture tests	
	Average ultimate strength, psi[a]	Conditions for failure stress, psi[b]	Conditions for no-failure stress, psi[c]
	Low strength, 4140		
80°F un-notched	135,000[d]		
80°F notched			
10,000 psi N_2	241,000 (4)		
6,000 psi H_2	207,000 (2)		
10,000 psi H_2	204,000 (3)	190,000 (30 sec)	185,000 (8)
		175,000 (9 hr)	170,000 (5)
250°F notched			
10,000 psi N_2	221,000 (2)		
6,000 psi H_2	207,000 (2)		
10,000 psi H_2	185,000 (1)	185,000 (3 min)	175,000 (6)
	High strength, 4140		
80°F un-notched	228,000 (2)		
80°F notched			
10,000 psi N_2	362,000 (2)		
2,000 psi H_2	135,000 (2)		
6,000 psi H_2	121,000 (4)		100,000 (5)
			110,000 (3)
10,000 psi H_2	89,000 (3)		70,000 (4)
			80,000 (4)
			90,000 (3)
250°F notched			
10,000 psi N_2	274,000 (1)		
2,000 psi H_2	92,000 (2)		
6,000 psi H_2	96,000 (4)		70,000 (5)
			80,000 (3)
10,000 psi H_2	82,000 (3)	65,000 (23 min)	
350°F notched			
10,000 psi H_2	103,000 (1)		

[a]Number of specimens shown in parentheses.
[b]Time shown in parentheses.
[c]Time in days shown in parentheses.
[d]Reported by the Bethlehem Steel Co.

The effect of purity of the hydrogen is most important. As little as 1% oxygen has been reported (24) to eliminate embrittlement in some alloy steels. Other impurities in the gas, which could combine with the metal to form a surface film presenting a barrier to the passage of hydrogen, would also be expected to be beneficial. Conversely, constituents in the gas stream which would be inert or which would attack the surface and prevent the formation of a barrier film would not have any beneficial effect, although possibly not a detrimental effect. If oxide films are developed, but are subsequently ruptured by plastic deformation, they would become ineffective in retarding hydrogen environment embrittlement. Some work has been done on protective coatings, but with limited success. The chief difficulties have been discontinuities or lack of adherence. Coatings are thin and could be damaged to the extent of destroying the protective effect by a momentary internal rub between rotating and stationary compressor parts, or by a foreign material passing through compressor in the gas stream.

The pressure of the hydrogen gas is an important variable, presumably at least in part as it affects the rapidity with which the gas can diffuse into an adva c-ing crack. In higher pressures where the gas penetrates the crack more rapidly, conditions favoring the progress of hydrogen environment embrittlement at the crack tip are reached more rapidly. Consistent with this, it has been observed that fatigue strength is reduced in hydrogen environments, and that crack growth rates are increased over those observed in air.

Prevention

It has been indicated that an important variable in determining the degree of hydrogen environment embrittlement is the yield strength of the material. In many cases gas streams which are high in hydrogen also contain hydrogen sulfide and moisture. As was discussed in a previous section, it has, in recent years, become quite common to apply a maximum yield strength specification. Most commonly the yield strength has been limited to 90,000 psi maximum. Immunity to hydrogen environment embrittlement has been achieved simultaneously with immunity to sulfide corrosion cracking.

Most of the research on hydrogen environment embrittlement has been conducted on materials having a yield strength of 180,000 psi or higher. When notched specimens have been tested both strength and ductility have been substantially reduced. This embrittlement has been observed to decrease with decreasing strength as reported by Cavett and Van Ness (21) by Steinman, Van Ness, and Ansell (22) and Deegan (25).

It cannot be said that the limit has been precisely defined, but it appears that yield strengths up to about 120,000 are acceptable in centrifugal compressors without undue risk of embrittlement. This effect may be

The shaft of centrifugal compressors is made from a heat treated low alloy steel, usually the same grades, AISI 4140 and 4340, as in impellers. It is often required that the yield strength be over 90,000 psi to accommodate the maximum applied stress under the coupling. At this location the shaft is not exposed to the process gas. The operating stress in the portion of the shaft inside the casing where it is exposed to the process gas is quite low —often under 5000 psi. For this reason, and taking into account data such as that previously cited from Warren and Beckman, the yield strength is usually not restricted.

Stationary parts including the casing and diaphragms made from carbon steel and cast iron meet the maximum strength and hardness requirements for immunity to sulfide cracking with margin to spare. Barrel type compressors for very high pressure service are sometimes made from low alloy steel forgings heat treated to yield strengths above 90,000 psi and hardnesses over Rockwell C-22, but the operating environment is not one likely to give rise to sulfide corrosion cracking.

HYDROGEN ENVIRONMENT EMBRITTLEMENT

Types of Hydrogen Environment Embrittlement

Another topic which has been of much interest in recent years is that of the effect of hydrogen in centrifugal compressors. The hydrogen problem takes three different forms which have been described by Jewett et al (14):

1. Hydrogen chemical reactions. This has also been called hydrogen attack, and occurs at elevated temperatures. The minimum temperature is usually cited as about 425°F. Material selection for elimination of hydrogen attack in steel is well documented by the Nelson charts (15). Hydrogen attack has not been a serious problem in centrifugal compressors. High temperature and high hydrogen conectrations have not often occurred simultaneously. When the temperature is high, the hydrogen content has been low and vice versa.

2. Internal hydrogen embrittlement. In this case delayed failure may occur, especially with high strength steels. Many examples are found in the manufacture of hardened and electroplated parts such as springs, washers, aircraft landing gear struts, etc. Internal hydrogen was also the cause of flakes in forgings which were involved in the failure of several large turbine and generator rotor forgings some 20 years ago (16, 17). The problem of flaking in large forgings has been eliminated with the use of vacuum degassed steel.

3. Hydrogen environment embrittlement. This is the aspect of the hydrogen problem which is of most significance in centrifugal compressors. As the name implies it occurs while the metal is stressed in hydrogen. Material exposed to high pressure hydrogen, but subsequently tested at room temperature does not exhibit this embrittlement.

Features of Hydrogen Environment Embrittlement

There has been an extensive literature developed on the last two forms of hydrogen embrittlement including papers by Elsea and Fletcher (18), Walter and Chandler (19), Beck et al (20), Cavett and Van Ness (21) and Steinman, Van Ness and Ansell (22). With all of the research, however, it has still recently been stated by NASA (23) "There are considerable gaps in the data available; essentially, no thresholds have been established for specific influences such as pressure, temperature, and stress much less the influence of combined factors." To this list might be added the effect of variations in gas composition.

There are several important distinctions between the last two types of hydrogen embrittlement. Internal hydrogen embrittlement does not show up immediately after charging the specimen, but will cause delayed failure if the specimen is held under a modest stress for a period of time. Hydrogen environment embrittlement, conversely, causes immediate embrittlement. Specimens usually fail during or very shortly after loading or not at all. In hydrogen environment embrittlement failures start at the surface while in internal hydrogen embrittlement cracks are initiated below the surface. Most of the time to failure in hydrogen environment embrittlement is in successive incubation periods. The incubation period before each step in crack formation is the time required for hydrogen to diffuse to the region of active crack progression.

Hydrogen environment embrittlement is sensitive to strain rate, because it requires the movement of hydrogen in the presence of a stress gradient. Conventional impact tests do not indicate embrittlement because the strain rate is high, and the time is too short to permit diffusion of hydrogen to the advancing crack tip. The effect is at a maximum at low strain rate, but the degree of embrittlement is independent of holding time under pressure (19) even when the specimens are held under stress in high pressure (10,000 psi) hydrogen.

Categories of Hydrogen Environment Embrittlement

Walter and Chandler (19) have separated metals into four categories according to the degree of embrittlement observed in high pressure hydrogen:

1. Extreme embrittlement. High strength steels and high strength nickel base alloys are in this category where embrittlement is characterized by a large decrease of notch strength and notched and unnotched ductility and some decrease in unnotched strength in 10,000 psi hydrogen. Metals in this category usually fail with one catastrophic crack which propagates into the specimen leaving a thin shear lip around the periphery except at the site of crack initiation.

2. Severe embrittlement. The majority of metals tested were in this category which includes most of the materials used in centrifugal compressors. Embrittlement is characterized by reduction of notch strength and notched and unnotched ductility, but little or no reduction of unnotched strength. Metals in this category usually fail with many surface cracks, some of which are quite deep.

3. Slight embrittlement. This category includes commercially pure titanium, copper, beryllium and the austenitic stainless steels having an unstable austenite structure. Embrittlement is characterized by a small decrease of notch strength and notch ductility. Metals in this category exhibit numerous small, shallow, blunt cracks, but low power magnification is required to see them.

4. Negligible embrittlement. Materials in this category include aluminum alloys, stable austenitic steels, and copper. They fail in the same manner in hydrogen

For these complex reasons it is difficult, if not impossible, to specify a threshold concentration of hydrogen sulfide in a gas below which sulfide corrosion cracking will not occur.

Effect of Temperature

A strong inverse relationship with temperature has been reported by Hudgins (13) with time to failure increasing markedly from 75°F to 150°F. Most centrifugal compressors with hydrogen sulfide in the gas operate at these temperatures or higher, particularly when the temperature rise through the machine is taken into account.

Service Experience

While the limits of 90,000 psi yield strength and hardness of Rockwell C-22 were selected for very aggressive environments, experience suggests that the environment in centrifugal compressors is considerably less aggressive. There are many welded AISI 4140 and 4340 low alloy steel impellers in service which were given a simple tempering treatment at 1100°F after fabrication, and which have suffered no distress, although the environments are known to contain hydrogen sulfide. Perhaps in these cases the operating temperature of the compressor is above the dew point of the gas so that liquid moisture is not present, or possibly the composition of the gas is such that the pH is greater than 7. A very recent paper by Garwood (11) has cited other cases where satisfactory service has been obtained in exposure to environments containing hydrogen sulfide at hardness values of Rockwell C-28.

In many of these cases the hardness of the base metal is approximately Rockwell C-26, and the hardness of the heat affected zone adjacent to the welds is Rockwell C 28-30. In one case, as reported by Moller (6), in ethylene off gas service there was cracking in the heat affected zone adjacent to some of the welds because of the omission of the 1100°F post weld heat treatment after repair welding. In this instance the hardness of the heat affected zone was Rockwell C 45-50. In the portions of the impellers which had not been repaired, and where the hardness of the heat affected zone was Rockwell C-30

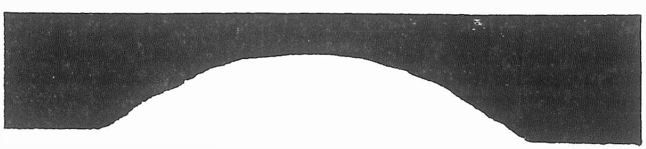

Figure 9. AISI 4140 Welded and Tempered Showing Heat Affected Zone.

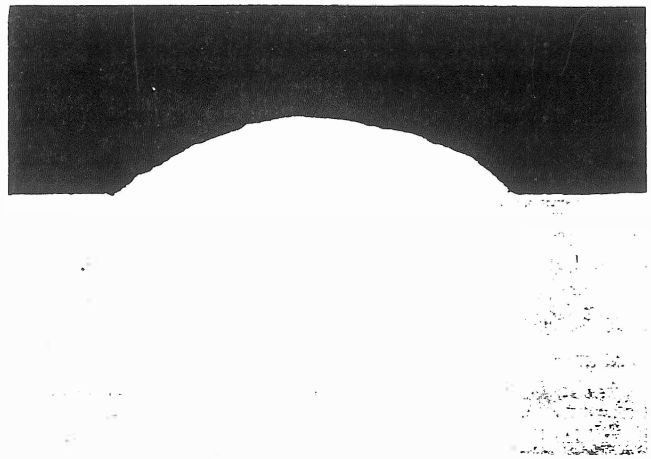

Figure 10. AISI 4140 Quenched and Tempered After Welding Showing No Heat Affected Zone.

or below, there was no cracking. It must be concluded that, in this instance, the severity of the environment was rather mild, and the common specification requirement of Rockwell C-22 maximum was not needed to prevent sulfide corrosion cracking.

Prevention

Compressor manufacturers are now equipped to perform a complete quench and temper heat treatment after fabrication by welding. When this is done, the heat affected zone disappears as is shown in Figures 9 and 10, and the impeller is of uniform hardness. With the use of such treatments, it appears safe to increase the maximum permissible yield strength up to at least 110,000 psi (9). In evaluating the maximum permissible yield strength, it is instructive to take into account the actual operating stress in centrifugal compressor impellers and its relationship to the yield strength. This stress increases with the square of the speed of rotation. According to API 617, it is required that impellers be overspeed tested, prior to assembly of a compressor rotor, at 115% of the maximum permissible continuous speed. The maximum continuous speed is in turn 105% of the design speed. Thus at overspeed the actual speed is 121% of design, and the stress at overspeed is 145% of the stress at design speed. For these relationships, refer to Table 3. Assuming the stress during overspeed testing approaches the minimum specified yield strength of the material, the stress at design speed woud be only 69% of this minimum yield strength. At maximum continuous speed rating the operating stress would be only slightly higher, still only 75% of the yield strength. These conservative stress values operate to reduce the risk of difficulty due to sulfide cracking.

TABLE 3. IMPELLER STRESSES AT VARIOUS SPEEDS OF ROTATION

Speed	Stress %	Speed %	Stress as % of Maximum Yield Strength
Design	100	100	69
Maximum Continuous	105	110	75
Trip	115	130	90
Overspeed	121	145	100

noting that in order for sulfide cracking to occur it is necessary that the following conditions be fulfilled:

1. Hydrogen sulfide must be present.
2. Water must be present in the liquid state.
3. The pH must be acid.
4. A tensile stress must be present.
5. Material must be in a susceptible metallurgical condition.

When all of the above conditions are fulfilled, sulfide cracking may occur with the passage of time. Failure is not instantaneous.

Inhibition

It is frequently not possible to remove the hydrogen sulfide or moisture from the gas. Some interesting work has been reported on the prevention of sulfide cracking by the addition of inhibitors; but, at least as far as centrifugal compressors are concerned, the use of these inhibitors does not seem to be widely practiced. Since enough time will always eventually be accumulated in any operating machine, the only variable which is capable of adjustment seems to be the condition of the material.

Metallurgical Condition

Numerous investigations have shown that the optimum microstructure for resistance to sulfide cracking is tempered martensite resulting from heat treatment by quenching and tempering. These studies have shown that low alloy steels having a maximum yield strength of 90,000 psi and a maximum hardness of Rockwell C-22 are not susceptible to sulfide cracking, even in the most aggressive environments. As the strength level increases above 90,000 psi, the threshold stress required to produce sulfide cracking may actually decrease in very severe environments. Warren and Beckman (10), for example, have reported that with a yield strength of 100,000 psi, the threshold stress required to produce sulfide cracking approached the yield strength, while at a yield strength of 140,000 psi the threshold stress dropped below 30,000 psi as illustrated in Figure 7. The test environment used

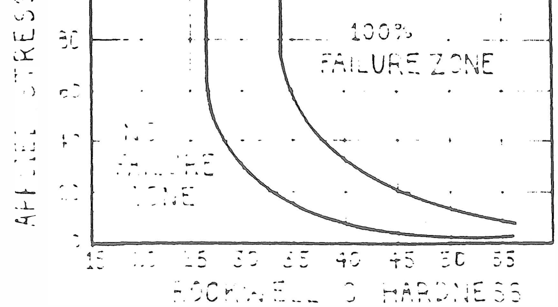

Figure 7. Threshold Stress for Sulfide Cracking as a Function of Hardness. (Ref. 10)

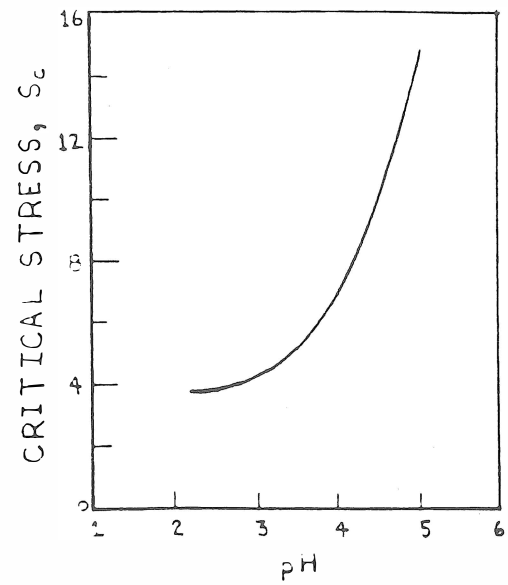

Figure 8. Critical Stress for Sulfide Cracking as a Function of pH. (Ref. 12)

by these authors involved a hydrogen sulfide water system at 104°F and 250 psi.

Effect of pH

Treseder and Swanson (12) have shown that the effect of pH is quite marked. For example, their experimental parameter increased from 4 at a pH equal to 2 to nearly 14 at a pH equal to 5 as shown in Figure 8. The importance of pH was also shown in the recent work by Keller and Cameron (9). Among the tests conducted in this work was a series on AISI 4140 which was quenched and tempered after welding to a base metal yield strength of 126,000 psi. The test specimens were stressed to 80% of the yield strength and tests were conducted in triplicate. At pH 2.5 all three specimens failed, while at pH 4.2 none of three failed. A similar series of tests was conducted on AISI 4140 which was quenched and tempered before welding to a base metal yield strength of 83,000 psi with only a tempering treatment at 1100°F after welding. Again the test stress was 80% of the yield strength. At pH 2.5, three tests were conducted and all failed. At pH 4.2 there were eight failures in nine tests, but at pH 6.5 there were no failures in three tests. The test environment was room temperature water saturated with hydrogen sulfide, and the pH was controlled by addition of hydrochloric acid or ammonia water.

The acidity of the gas in a compressor is determined by condensing a sample of the gas and making a pH determination. When the concentration of hydrogen sulfide is sufficient to saturate the water, the pH value is about 4.3. If the hydrogen sulfide present is not sufficient to saturate the water, the pH will be higher. Further, the pH may be influenced by the presence of other constituents in the gas stream which are soluble in the water. Hydrogen chloride, for example, is capable of depressing the pH to values well below 4.3 and accelerating attack. Other possible constituents could reduce the acidity, raise the pH, and reduce the severity of attack.

in hydrogen reformer compressors, but these were attributed to improper heat treatment resulting in a high level of internal stress. Since that time many additional impellers have been fabricated using improved heat treating practices, and there have been no further difficulties. With Monel K500, as with the austenitic stainless steels, allowance must be made for the high coefficient of thermal expansion. The yield strength of Monel K500 is considerably higher than that of the austenitic stainless steels making it possible to use heavier shrink fits with Monel K500.

Compression of halogen gases, and especially chlorine, presents an interesting problem. If the chlorine is truly dry, standard materials may be used quite satisfactorily provided that the temperature is kept below about 275°F (3). In a few instances with wet gas, chlorine compressors have been built completely from unalloyed titanium. The impellers were of the open-inducer type. The casings were vacuum cast in graphite molds, and the casing volute casting had a cleaned weight of 1800 lbs. While titanium is exceptional for use with wet chlorine, it cannot be used in dry chlorine, because in the event of a rub which would generate an elevated temperature, titanium is pyrophoric. This characteristic can be suppressed with moisture in the chlorine, and the generally accepted minimum moisture content is 0.015%.

Aluminum alloy compressor impellers have been used in great numbers, but in a limited range of applications. A steady stream of higher strength aluminum alloys is becoming available, and the applications may be expected to increase. Limitations on use of aluminum alloys have been 1) decrease in strength above about 300°F, and 2) difficulties in fabricating closed impellers from the high strength compositions. Integral cast closed impellers have been used extensively in such applications as diesel turbochargers, refrigeration compressors, and some centrifugal compressors on air. Aluminum alloys are avoided in impellers for oxygen service. In the event of a rub between the rotating and stationary parts causing the aluminum to reach a high temperature, there is a possibility of a thermit reaction with oxides on the surface of iron or steel parts.

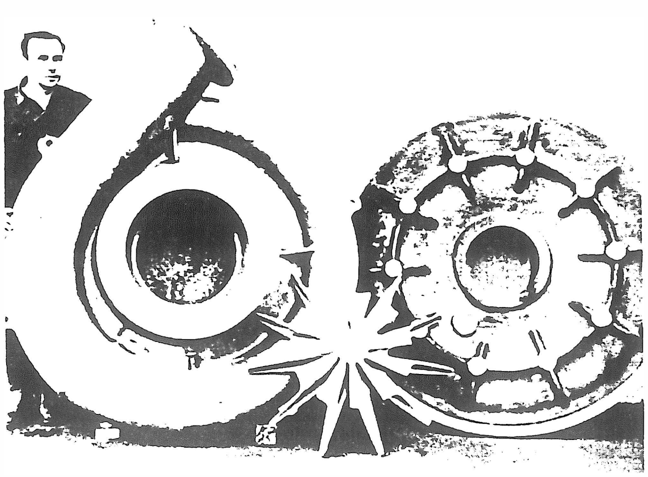

Figure 6. Titanium Castings for Compressor Handling Wet Chlorine.

Both aluminum and titanium are sometimes selected for centrifugal compressor impellers because of their low density, even in environments where corrosion will not occur. The lower density causes a shift in the critical speed of a rotor which may be very advantageous.

Coatings

Coatings for the prevention of erosion and corrosion of steel compressor impellers have been used, but only sparingly. A few machines have been built with a coating of electroless nickel, and while service to date has been rather brief, results seem to be satisfactory. Limited use has also been made of organic coatings such as one of the phenolic resins. The usual concern with coatings of this sort is durability. Most compressor users do not want to open the machine for recoating of parts more than once every two or three years, and it has not been possible to give assurance that coatings will last this long. In one application involving air containing finely divided water droplets and some sulfide dioxide, a phenolic coating has performed satisfactorily when renewed at intervals of about six months. In this case the machine is of the single-stage type where the impeller can be changed more readily than is the case with multi-stage compressors.

Open type impellers are much easier to coat than fully closed impellers. The difference is primarily in ease of cleaning. Most coatings require a white finish abrasive blast cleaning, which is difficult because of poor accessibility in fully closed parts. It is impossible in closed impellers of low passage height. Most coatings, and especially those requiring baking for curing, are very intolerant of discontinuities such as sharp corners or porosity in the surface being coated.

Aluminum alloy impellers in plant air compressors are almost universally anodized. Conventional anodizing is sometimes employed, but more commonly impellers are hard anodized to obtain a coating having greater thickness and hardness than conventional anodizing. This hard anodizing provides protection from both corrosion and erosion.

SULFIDE CRACKING

Background

In recent years there has been a great deal of interest in the possibility of sulfide cracking in centrifugal compressor impellers. There is extensive literature on sulfide cracking in oil well casing materials (4) going back some twenty years. Incidents involving centrifugal compressors have been rare, as reported by Kohut and McGuire (5) and Moller (6). Nevertheless, the subject is, justifiably, one of serious concern because of the potential of a failure and loss of service of a vital link in the production chain of a chemical or petrochemical plant. Greer (7) has recently presented an excellent paper describing the effects of more than a dozen variables on resistance to sulfide corrosion cracking. Other investigations dealing specifically with sulfide cracking in compressor impellers have been reported by Scheminger, Ebert, and Aul (8) and by Keller and Cameron (9).

Essential Features

While it is impractical to attempt to review all of the data in detail, the salient points may be summarized by

TABLE 1. CHEMICAL ANALYSES OF IMPELLER MATERIALS

	AISI 4140	AISI 4340	AISI 410	AISI 304	AISI 316	Armco 17-4PH	Monel K-500
Carbon	0.38-0.43	0.38-0.43	0.15 max.	0.08 max.	0.08 max.	0.07 max.	0.25 max.
Manganese	0.75-1.00	0.60-0.80	1.00 max.	2.00 max.	2.00 max.	1.00 max.	1.50 max.
Chromium	0.80-1.10	0.70-0.90	11.50-13.50	18.00-20.00	16.00-18.00	15.50-17.50	....
Molybdenum	0.15-0.25	0.20-0.30	0.50 max.	....	2.00-3.00	....	....
Nickel	....	1.65-2.00	0.50 max.	8.00-12.00	10.00-14.00	3.00-5.00	63.00-70.00
Copper	....	....	....	....	....	3.00-5.00	Remainder
Columbium	....	....	....	....	....	0.15-0.45	....
Aluminum	....	....	....	....	....	....	2.00-4.00
Titanium	....	....	....	....	....	....	0.25-1.00

tensile properties of these and other impeller materials are listed in Tables 1 and 2.

The forgings are heat treated to the desired strength level, Table 2. After machining and welding, impellers are heat treated for the purpose of tempering the heat affected zone in the base metal adjacent to the welds. The base metal hardness varies with the yield strength required, but is frequently about Rockwell C-26. In the heat affected zone immediately after welding the hardness can be as high as Rockwell C-45 or 50. After tempering at 1100°F this value falls to Rockwell C-28 to 30. The use of more complex post weld heat treatments will be discussed later, but when a simple tempering treatment is employed, the temperature cannot be higher than 1100°F because this is the minimum tempering temperature for impeller hub and cover forgings. A post weld heat treatment at a temperature above the minimum tempering temperature for the forgings could result in a loss of strength in the hub or cover base material.

Special Materials

Where more corrosion resistance is needed than is available from ordinary low alloy steels, such as in some chemical and petrochemical process gas compressors containing moisture and corrosive gases, the next step in improved resistance is usually AISI Type 410 stainless steel which contains about 12% chromium, as shown in Table 1. Weldability of Type 410 is comparable to that of the low alloy steels.

A further improvement in corrosion resistance for more aggressive environments can be obtained through the use of one of the precipitation hardening stainless steels such as Armco 17-4PH or 15-5PH.[b] These grades, while appreciably more expensive, also have the advantages of further improved corrosion resistance as compared with Type 410, and much improved weldability. The precipitation hardening grades also have higher strength than Type 410 stainless steel, and are sometimes used for this reason where the corrosion resistance of Type 410 would be adequate.

The austenitic stainless steels, such as Type 304 and Type 316, Table 2, are occasionally used in the low tip speed impellers for single stage centrifugal compressors, but very seldom in multi-stage machines. The corrosion resistance is attractive in certain environments, but the yield strength of these materials is only about 30,000 psi imposing a rather severe limit on tip speed, and precluding their use for most applications. A further deterrent is the high coefficient of thermal expansion which creates difficulties with rotors built up by shrinking impellers on shafts. The coefficient of thermal expansion of the austenitic stainless steel impeller is about 50% greater than that of the usual low alloy steel shaft. If the temperature excursion during operation is sufficient, the differential growth may cause the impeller to come loose on the shaft. A heavy shrink fit cannot be used to offset this problem because of the low yield strength of the material.

Usually the temperature excursions in single stage compressors are such that the differential coefficient of expansion can be handled, and these materials have given considerably improved resistance to such gases as sulfur dioxide.

Another material which has been used for centrifugal compressor impellers is Monel K500.[c] This material has been used chiefly for exposure to halogen gases in the moist condition, and the record is generally good, although corrosion rates sometimes are high enough to require occasional replacement. It has also been used because of its resistance to sparking in oxygen compressors. Some 20 years ago there were several failures

(b) Armco Steel Corporation trademark

(c) International Nickel Company trademark

TABLE 2. TYPICAL PROPERTIES OF IMPELLER MATERIALS

Material	Ultimate Tensile Strength	Yield Strength 0.2%	Elongation %	Reduction in Area, %	BHN
AISI 4140	100,000 psi min.	80,000- 90,000 psi	16 min.	50 min.	212-235
AISI 4140	115,000 psi min.	95,000-120,000 psi	16 min.	50 min.	269-321
AISI 4340	120,000 psi min.	105,000-120,000 psi	17 min.	43 min.	248-302
AISI 4340	125,000 psi min.	115,000-135,000 psi	16 min.	50 min.	269-321
AISI 410	100,000 psi min.	80,000- 90,000 psi	14 min.	40 min.	212-235
AISI 304	75,000 psi min.	30,000 psi min.	40 min.	50 min.	205 max.
AISI 316	75,000 psi min.	30,000 psi min.	40 min.	50 min.	217 max.
Armco 17-4PH	130,000 psi min.	105,000 psi min.	16 min.	50 min.	277-341
Monel K-500	130,000 psi min.	90,000 psi min.	20 min.	....	250 min.

The same welding procedures may be used as in 1 above. Theoretically it would be possible to reduce the fillet size and thereby increase the area of the aerodynamic passage, but in practice this reduction is small.

Number 3 has a partial blade machined integral with the hub and cover and a butt weld down the middle. This procedure has been used successfully, but is more difficult than it appears, especially in blades having high backward lean angles, and there is some difficulty in achieving a satisfactory weld contour around the leading edge of the blades.

Number 4, slot welding, is used chiefly as an alternate to fillet welding in applications where the gas passage height is too shallow for accessibility, or the backward lean angle is too high to permit conventional fillet welding from the periphery of the impeller. This weld may be deposited by tungsten arc inert gas, metallic arc inert gas, manual metal arc, submerged arc welding, or a combination of these. As compared with fillet welding, there is a considerable increase in the amount of weld metal that must be deposited, and therefore, in welding time. Compensating for this to some extent is the lesser intrusion of the weld into the aerodynamic channel. As already mentioned, impellers that cannot be fillet welded can be fabricated in this manner. Impellers may be slot welded to either the hub or cover. On the component opposite to that slot welded, blades may be attached by fillet welding, or they may be cast integrally with the hub or cover.

Number 5 shows a hub or cover electron beam welded to a blade. While a good deal of experimental work has been done, production experience with electron beam welding of impellers is limited. The chief problem has been extension of the interface between the blade and hub or cover from which a crack can propagate into the weld on cooling as shown in Figure 4. There is an operational problem in maintaining preheat during the time required to evacuate the welding chamber. Possibly this could be overcome using quartz lamps or a defocussed electron beam to preheat. Electron beam welds should preferably be stressed in tension, but the configuration of the part in this case produces a stress in shear. Inspection of these welds is very difficult. In addition, capital equipment cost is very high and utilization of the equipment is low.

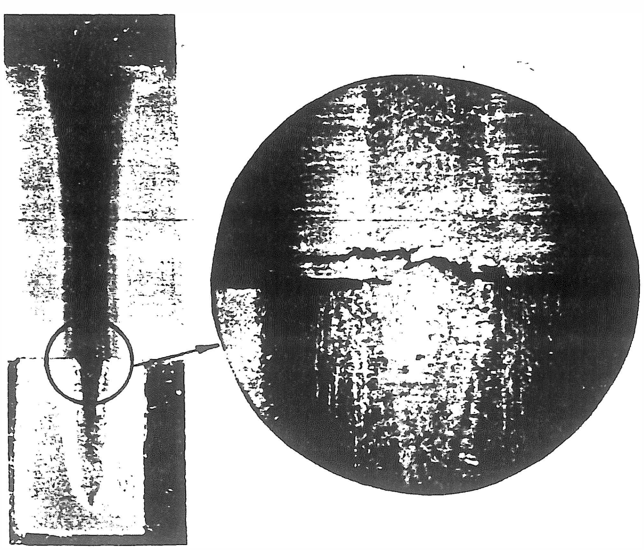

Figure 4. Electron Beam Weld Showing Interface Cracking.

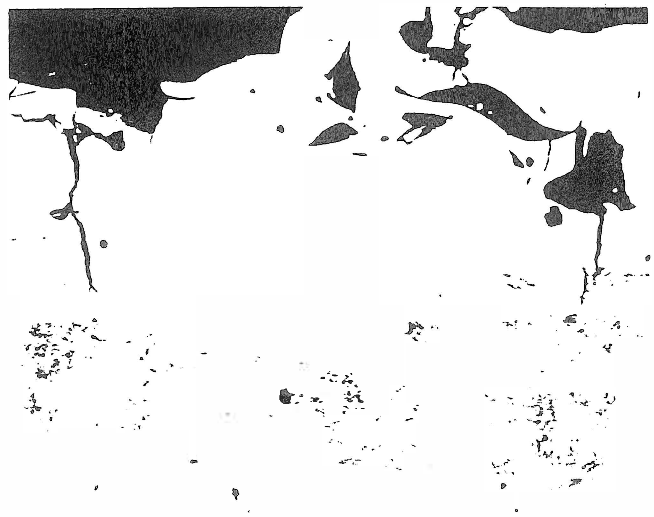

Figure 5. Recast Layer on Electrodischarge Machined Surface.

Number 6 illustrates a construction without welding where the impeller is made from a one piece casting or machined from a solid forging, possibly by electrodischarge machining. In one piece castings, the tooling cost is very high to provide for varying channel heights and impeller cover eye openings. Electrodischarge machining is a relatively slow process, and produces what is known as a recast layer on the surface of the part, Figure 5. Studies have shown that this recast layer can reduce the fatigue strength of the part by as much as 60% unless it is removed by careful grinding (2).

Number 7 shows various configurations of riveted blades which have been used. In comparison with welded construction, the riveted parts are less strong, and there is a potential source of fatigue cracking due to the stress concentrations around the rivet holes. Numbers 7a and 7b have rivet heads which protrude into the aerodynamic passage detracting from the cleanliness of this passage. If there is any dirt in the gas being compressed, it can hang up, and may cause balance or corrosion problems.

IMPELLER MATERIALS

Usual Materials

Impeller disc and cover forgings are usually made from a low alloy steel, such as AISI 4140 or 4340. The final selection of the particular low alloy grade for each application depends on the strength level desired and the size of the impeller. AISI 4140 is satisfactory for most applications; AISI 4340 is used for larger impellers or higher strengths because of greater hardenability and resistance to tempering. The greater resistance to tempering makes it possible to achieve higher yield strength while maintaining a relatively high tempering temperature with 4340 as compared to 4140. The usual minimum permissible tempering temperature is 1100°F, which makes possible a good balance between strength, toughness, and low internal stress. Chemical analyses and

ASPECTS TO BE CONSIDERED

It would be impractical, in one discussion, to attempt to cover all of the aspects of centrifugal compressors involving metallurgical considerations. A few of those which are of most current interest have been selected:

1. Impeller fabrication.
2. Impeller materials.
3. Sulfide corrosion cracking.
4. Hydrogen embrittlement.
5. Brittle failure.
6. Dimensional stability.

IMPELLER FABRICATION

Types of Impellers

The heart of a centrifugal compressor is the rotating element, and a great deal of attention is given to the fabrication of centrifugal compressor impellers. Fully shrouded impellers having solid back wall and cover, as shown in Figure 1, are the most common type in multi-stage centrifugal compressors. Impellers of this type present more difficult fabricating problems than the open or semi-closed type shown in Figure 2, more commonly used in single stage machines. For this reason, attention is focused primarily on the fully closed impellers.

In most cases, centrifugal compressor impellers are fabricated from materials which are ordinarily considered difficult to weld; but, satisfactory techniques have been developed. Thousands of impellers have been fabricated successfully; in fact, the history of impeller welding goes back more than thirty years. There have been changes and improvements in materials and processes through the years. Probably the most significant advance was the advent of low hydrogen materials and processes. Prior to the development of low hydrogen welding materials, one of the most difficult problems was that of delayed cracking. Impellers that apparently were sound immediately after welding would occasionally be found to be seriously cracked after standing at room temperature for periods ranging from a few hours to a few days. Also, earlier impeller forgings were usually made from acid open hearth steel with relatively high phosphorus and sulfur contents. In more recent years this practice has been changed. Lower impurity basic electric furnace steels are now used, and weldability has been improved (1).[a]

(a) Numbers in parentheses refer to the list of References

Figure 1. Typical Fully Shrouded Impellers.

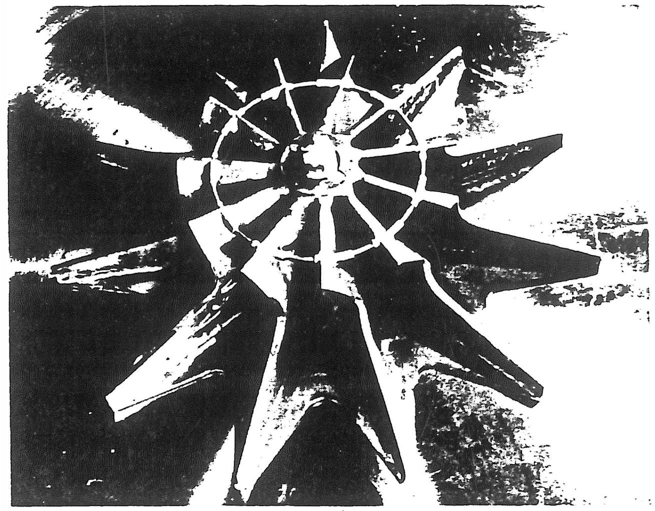

Figure 2. Typical Fabricated Open Impeller.

Methods of Fabrication

Several methods of fabrication are shown in Figure 3. Number 1 in this figure illustrates construction in which blades are fillet welded to the hub and cover. This is the most common method of fabrication. Welding may be done by manual metal arc, gas shielded metallic arc, submerged arc, or firecracker procedures. Welds are readily inspected using magnetic particle methods on magnetic materials and liquid penetrant methods on non-magnetic materials. This method of fabrication has the advantages of being the least costly welding procedure and requiring the least capital equipment cost. The chief disadvantages are poor accessibility when the gas passage height is low, or the backward lean angle is high, and the intrusion on the aerodynamic passage of the fillet welds.

Number 2 is similar to Number 1 except that the welds are full penetration. This is a more costly welding procedure, which seems to offer few, if any, advantages.

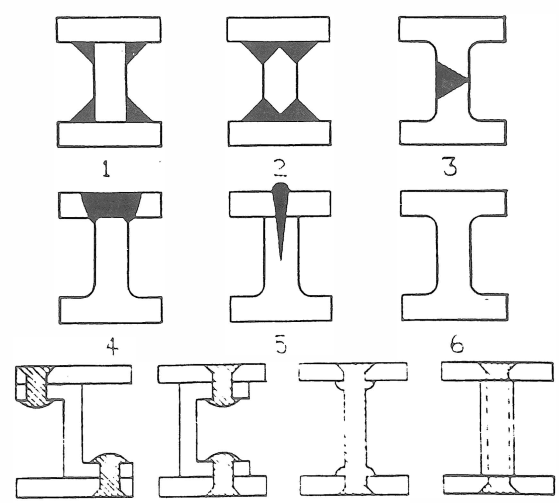

Figure 3. Methods of Impeller Fabrication.

4330, which is lower in nickel but higher in chromium and molybdenum, has become almost universal. The impact requirements can be met more readily with the 43XX series because of increased hardenability and better response to heat treatment (30). Below −150°F recourse must be had to other materials such as the 5% nickel steel recently developed by Armco under the tradename Cryonic 5[d] or the 8 or 9% nickel steels. As previously mentioned, 9% nickel steel has been used for some years quite successfully at temperatures down to −320°F in both rotating and stationary applications. For some applications aluminum alloys have also been used successfully. These temperatures are becoming increasingly of interest in connection with liquefied natural gas projects.

STABILITY

One of the most insidious problems that can occur in the manufacture and use of turbomachinery is dimensional instability. When instability is encountered during manufacture it may be impossible to achieve required close tolerances on stationary parts and concentricity on shafts. Long term instability which may occur in service can cause leakage at casing joints, or a rotor to go out of balance with resulting excessive vibration.

Casings

Instability leading to difficulty in manufacture can occur with centrifugal compressor casings, but in practice is not a major problem. Casings of either the cast or fabricated type are given a stress relief heat treatment during manufacture at about 1100°F, a temperature which insures a low level of internal stress. Generally there is more difficulty with distortion during machining of castings than fabricated casings. The wall thickness of castings is tapered in order to achieve progressive solidification of the casting, with the result that the amount of metal removed in machining is not equally distributed. This tapered thickness is not encountered with fabricated casings. The amount of material removed in machining is more uniform, and usually less than with castings. Further, castings require substantial amounts of repair welding. Defects which are encountered during final machining, and which require welding are particularly troublesome.

Long term service instability of compressor casings is very seldom encountered, and for this reason literature in this area is non-existent. This type of instability is more commonly encountered with turbines because of the higher operating temperature, greater temperature excursions in service, and higher thermal gradients. In addition, particularly with modern high temperature, high pressure turbines, the wall thickness of the casing is greater. Several papers, including one by Reisinger and Scharp (31) have been published on the subject of steam turbine casing distortion and cracking due to thermal gradients. Precautions are taken to avoid this by the use of slower heating and special design features in the casing.

Other internal stationary parts in centrifugal compressors, such as diaphragms, are most commonly made from cast iron. Occasionally when higher strength is required, ductile iron or fabricated mild steel is used. In all cases the castings or fabrications are treated to produce a low level of internal stress, and difficulty with instability in service is virtually unknown.

(d) Armco Steel Corporation trademark

Rotating Parts

Rotating parts for centrifugal compressors are, likewise, carefully treated in order to insure a low level of internal stress. Shafts made from quenched and tempered alloy steels such as AISI 4140 or 4340 are tempered at a minimum temperature of 1100°F, and difficulty with achieving concentricity during manufacture is rarely encountered. As in the case of stationary parts, the problem is a good deal more serious with turbines, and, again, published literature on this problem generally deals with turbines. For turbine rotors with integral discs, a vertical heat treatment is recommended. Further, such rotor forgings are tested for thermal stability in a special test apparatus where the rotor may be rotated at a speed of about 2 rpm while being heated to a temperature of about 1000°F with the eccentricity being measured by the use of dial indicators having long extension arms reaching into the test furnace.

Possibly the most common cause of true instability is due to a deficiency in prior heat treatment with the result that the material on one side of the shaft has a coefficient of thermal expansion different from that on the other side by about 1%. This is sufficient to cause a significant deflection when the shaft is heated to 800-1000°F. This and other possible causes of instability have been discussed at length in two excellent papers by Barker and Jones (32) and Timo and Parent (33).

SUMMARY

A brief look has been taken at a number of metallurgical considerations in the manufacture and use of centrifugal compressors. These have included impeller fabrication, impeller materials, sulfide cracking, hydrogen embrittlement, and stability. In each case the potential problems have been outlined, and the measures taken by the manufacturers to achieve a long satisfactory life for the user have been discussed.

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