High temperature brazing development since the time of the "Bow-Tie Generation": In memory of Robert L. Peaslee

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Entwicklung von Loten für das Hochtemperaturlöten seit der Zeit der „Frackschleifen-Generation“: zur Erinnerung an Robert L. Peaslee

Enormous technological progress in brazing development has occurred since R. Peaslee’s discovery of Ni/Cr-B-Si brazing filler metals (BFM) in 1947. The major steps in finding new BFM compositions and methods of joining were achieved in the first 30 – 40 years since then. The discovery that rapid solidification (RS) technology can convert inherently brittle alloys in conventional form into ductile ribbon should be considered as one of these steps. The present paper is an attempt to highlight a few episodes in the continuing evolution of brazing technology. First, BFM classes will be described along with their recent modifications. The modern understanding of the brazing mechanisms will be briefly presented afterwards. This will be followed by descriptions of novel methods of BFM placements, the status of the transient liquid phase (TLP) joining and joint loading, and brazing technology utilization for turbine parts repairing. Particular attention will be paid to new fast-growing and topical brazing application areas that are associated with energy conservation and environment protection. These latest applications are characterized by employment of thin-walled three-dimensional compact and economical honeycomb structures. Here thin flexible preforms with uniform thickness are required for covering large cross-section areas of the parts to be brazed. The utilization of RS amorphous foil is well suited for use in many of these brazing applications areas.

1 Introduction

A qualitative leap in development of brazing filler metal (BFM) technology occurred during and shortly after WWII as part of enormous progress in the field of metallurgy. This progress was spurred on by the development of jet airplanes, atomic weaponry and energy, etc. The occurring technological progress required a dramatic increase in materials performance particularly at high temperatures and in highly corrosive environments. It seems logical that in 1947 R. Peaslee discovered another application for Ni/Cr-B-Si hard-facing alloys as a new BFM class in his attempt to braze turbine disks on the recently developed jet airplanes [1]. These hard-facing alloys had been previously used for the gear enhancement of the propeller-driven airplanes. Peaslee needed brazements which could work at much higher temperature than that in engines providing power to all propelled airplanes of this time. The then existing BFMs were made with silver and gold and could not satisfy industry demands.

The next 10-20 years saw the development of dozens of new and modified BFM’s for practically all classes of steels and alloys. The major achievements in this respect were made mostly in the US. The late seventies were notable for the formation of strong metallurgical schools in Germany. These schools were established by Profs. H. Steffens and E. Lugscheider. Researches trained at these schools made continuing significant and creative contributions to joining science and technology since then.

The most comprehensive overview of the status of high temperature brazing technology was written by H. Pattie in late seventies [2]. In the same time E. Lugscheider and K. Gundlfinger published a review of mechanical properties of brazed joints produced from virtually all known iron- and nickel-based steels and alloys used as the base metals [3]. It is remarkable that very few if any principally new and important BFM compositions and innovations in brazing technology development have been developed since then. On a positive side it is worth noting that a much better scientific understanding of brazing mechanisms has developed. Brazing technology has also been employed in new industrial applications.

The current short paper is not an attempt to give a complete review of what has been accomplished in the last few decades. Only a few episodes subjectively chosen and related to steels and alloys joining will be presented. Titanium joining considered recently in [4], composites, and ceramics are left out of the paper scope. The paper will begin with an overview of existing classes of BFM with notes on the newest compositions that have been added to excising ones. Then the modern outlook on metallurgical paths of joint formation will be given. Particular attention will be paid to very recent expansion of brazing applications in industry.

2 General outlook

2.1 BFM Compositions

All current BFMs can be split into two major classes according to their nature, namely, eutectic and solid solutions (Table 1).

2.1.1 Eutectic alloys

These alloys are produced from transition metals (TM) such as nickel, iron, cobalt, and chromium, etc. in combination with metalloids, such as silicon, boron, phosphorus, and carbon. In the conventional crystalline state all these materials are inherently brittle and cannot be produced in continuous forms such as foil, wire, etc. Therefore, they are available only as powders or their derivatives.

During the last 10 years new alloys have appeared on the world market with compositions which are modifications of previously known ones. These alloys contain phosphorus as the major metalloid added to (Ni, Fe,Cr)-base [5-9]. Phosphorus depresses alloys' melting characteristics more strongly than boron and silicon: For example, in Ni-B alloys T_{liq} drops on 21 °C with addition of 1 at.%B whereas in Ni-P alloys-on 31 °C/at.%P. The partial or complete replacement of boron and silicon with phosphorus permits the increase of the amount of iron, chromium and molybdenum without increasing the melting temperature above 1150–1200 °C. As a consequence, these alloys have a large chromium concentration providing good corrosion resistance. They also have two economical advantages: (a) They have a lower cost because of the nickel replacement with Fe and (b) They can be employed, -due to their low melting temperature,- using low cost belt furnaces with protective atmospheres instead of vacuum ones. Some phosphrus-containing compositions can also be cast in amorphous ductile foil. These are produced by Metglas Inc. [10] and Vacuumschmeltze [9].

Table 1 Commercial and *developmental* brazing filler metals (BFM) for joining steels and metal alloys at T_{BR} >900°C

Alloy System	Alloy Class	Major Alloying Elements	Forms	T_{BR}, ˚C	Service Temp., ˚C
Trasition Metal-Metalloid Alloy Systems					
Ni/Fe/Co-(B)-(Si)-(C)-(P)	**Eutectic**	**Cr, Mo, W, Ti, Al**	**Powder Paste Tape, RS Foil**	**950-1200**	**≤1200**
Ni/Pd-(Si)-(B)	**Eutectic**	**Cr, Co, W, Mo**	**Powder Paste Tape, RS Foil**	**900-1000**	**400-800**
Trasition Metal-Metal Alloy Systems					
Ni-(20-23)Ge	***Eutectic***	***-***	***Powder, Paste***	***~1200***	***>1200***
<u>Ni/Zr/Hf</u>	***Eutectic***	***Cr***	***Powder, Paste***	***1200 - 1250***	***>1150***
Noble Metal Systems					
Au/Pd/Ag	**Solid Solution**	**Cu, Ni, Cr**	**Powder, Foil, Wire**	**900-1300**	**≤1200**

The successful application of alloys containing P in addition to B and Si by the Alfa-Laval group brought them to an unjustified conclusion that a new, so-called "AlfaFusion", brazing mechanism has been found. They advertize "AlfaFusion" as never before observed combination of welding with transient liquid phase (TLP) processing [5]. Because the brazing temperature in " AlfaNova" process is lower than the BM melting temperature the process cannot be charcterized as "classical" welding. At the same time the goal of the TLP process is to minimize or complete eliminate of the eutectic zone in the joint microstructure. In fact, very wide eutectic structure zones are present in Alfa-Laval brazes upon crystallizaiton. This is a result of considerable brazing gap loading with BFM powder ensuing a very strong erosion of thin stainless steel parts and the formation of a wide eutectic zone witrhin the braze. Similarly strong BM erosion with positive resuls occurs in the case when a very thin, 50-µm Fecralloy foil is brazed with 20 µm-thick Ni-19Cr-1.5B-6.5 Si (MBF-50 amorpous foil) [11]. Here the base metal erodes on more than 50% of its virgin thickness with a formation of a similarly wide eutectic zone. Still a high joint strength and very good corrosion resistance are obtained in Fecralloy/MBF-50 case due to formation of precipitation-strengthened eutectic joint micro-structure. Fecralloy/MBF-50 brazements have been used in production of **M**etal **C**atalist **S**upports (MCS) for more than two decades. It is fair to say that the experimental data shows no new features of the traditional brazing mechanism in both "AlfaFusion" and Fecralloy/MBF-50 cases.

2.1.2 On boron controversy

According to R. Peaslee literally from the first day when Ni-B-Si alloys were proposed for brazing he fought to get permission for their testing. At that time boron was considered as a harmful impurity in analogy with its role in steels. Since then the outlook on boron has changed substantially. Still, some applications specifications exist in which the use of boron is prohibited.

Meanwhile, the presence of boron decreases the liquid metal surface tension and, therefore, strongly increases wetting and flow. It increases the BM dissolution rate. More importantly, boron is uniquely responsible for the amorphability of Ni-B-Si alloys. Alloys should contain at least 1.4 wt. % B in addition to Si to preserve liquid atomic structure upon RS.

Boron rapidly diffuses in the solid BM thus decreasing its amount left in the joint which can form chromium borides in the joint eutectic. The fast boron depletion assists joint isothermal solidification. In this case, – if the BFM also contains silicon, – the joint may have ductile and strong (Ni,Cr,Si) solid solution matrix phase under properly chosen brazing conditions [12]. Such structure may have the strength on the level of that of the virgin base metal. If Ni-based BFM contains no silicon, as in the Ni-15Cr-3.75B (BNi-9 or MBF-80 foil with similar composition) then the ultimate joining goal may be achieved, namely, parts are joined with minimal or no traces of brazing. On the other site, boron is practically unsolvable intergranularly in highly alloyed materials used as the base metals. It segregates at BM grain boundaries thus making BM prone to brittle failure. It also depletes BM grain boundary interface zones from Cr and concentrates Cr in Cr_xB_y thus affecting BM corrosion and oxidation resistance. These negative effects can be corrected via optimization of heat treating and employing compositions with only 1.3–1.5 wt. % B [12]. Meanwhile, it is worth to mention that 300B-series austenitic stainless steels with very high, >2 wt. % B average are safely used for pipes in atomic reactors where high neutron absorption of boron is necessary [13]. This is a good example of an application where the huge presence of chromium borides doesn't create any concerns if properly addressed.

2.1.3 New Ni-Ge and Ni-Zr/Hf compositions

Recently, there has been growing interest in using Ni-base alloys with either Ge or Zr/Hf/Cr additions which are also eutectic [14-20]. These alloys have been mostly developed for repairs of turbine blades and have to withstand high service temperatures.

Ni-(20-23) Ge alloys were tested as new BFMs for diffusion brazing of single-crystal superalloys [14]. It was proved that germanium can be used as a new melting point depressant in these materials. It also assists in γ/γ‘ microstructure formation throughout the whole superalloy braze. More impressively, the original single crystal structure orientation is preserved and it is the same in both parts and the joint. However, the brazing time needed for completing this process stage is substantially longer than that required when using boron-containing BFMs.

Ni-Zr/Hf alloys have rather high melting temperature and their joints have high strength and good corrosioin and oxidation resistance [15-19]. Their eutectic structure consists of Ni-based matrix phase and various intermetallic phases formed between Ni, Zr, Hf and Cr. These intermetallic phases have lower hardness and are much more ductile in comparison with intermetallic phases forming in the Ni-B-Si-based BFMs [16]. The microhardness of phases varies slightly across the joint -another good feature of these alloys. So far, Ni-Zr/Hf alloys with up to 25 wt.% Hf have been applied for reparing vanes and blades in which wide brazing gaps need to be filled [17].

2.2 Solid solutions alloys

Solid solution alloys are made of silver and gold as the bases to which Pd, Ni, and Cu are added. These alloys are very malleable and can be produced in foil and wire forms. They possess an outstanding resistance to oxidation and corrosion. This group has rather limited application due to relatively low joint strength at high temperatures and the high cost of its noble metal components. No principally new composition(s) had been appearing on the market recently.

2.3 Modern approach to the joint formation

In current well-accepted analysis the brazing processes are considered in terms of its inherent connection with paternal binary and multi-component phase diagrams of both base metals and BFM. In the last decades a lot of thermodynamics assessments of multi component diagrams were made in direct attempt to link these data with TLP parameters [21, 22].

Due to the complexity of such assessments experimental results still differ from the calculated ones [21]. Furthermore, no reliable phase diagrams that present alloy systems with more than 4-5 major components exist in literature. Meanwhile, real metallurgical cases existing in modern superalloy brazing involve a minimum of 5-6 major components. However, even a simplistic analysis of existing binary and ternary phase diagrams can be useful in providing good guidance for the metallurgical paths by which the joint microstructures develops and in elucidating the reasons for the appearance of certain phases. Moreover, it provides the most effective way for establishing conditions for joint structure/properties optimization [23].

Thus when considering, for example, formation of transition metal borides in brazements, it is worth to take into account the constitution of known paternal binary and ternary phase diagrams. Accordingly, Cr dissolves Ti, Mo and W in solid solution state in a wide area of concentration [24]. The same is true for their borides. This readily explains why complex chromium borides $(Cr,Mo,W,Ti)_x B_y$ are formed in joints of superalloys containing these elements when they are brazed with Ni/Co-B-Si [25]. In the same vein binary and ternary phase diagrams show that silicon dissolves significantly in the (Ni,Cr) γ-phase forming (Ni,Cr,Si) solid solution. This is in sharp contrast to boron which has practically no solubility in Cr and Ni. When materials containing boron are brazed, they form a series of borides at BM grain boundaries with an increasing fraction of boron in the Cr_xB_y compounds when the initial B% is increased.

Therefore, the following may be expected and indeed observed in joint eutectic structures arising in the case when Ni/Fe/Cr-based BM is brazed using (Ni/Cr)-B-Si-based BFM joints:

- Formation of complex chromium/transition metal borides in both affected BM and the joint solid solution matrix phase but the lack of Ni borides.
- High sensitivity of the joint structure to the initial BFM silicon concentration: when the silicon concentration is low the (Ni,Si)-solid solution matrix phase provides high strength combined with ductility [26]. This can occur because there is

either a low initial %Si in the BFM, or/and the brazing process is carried out over a sufficiently long time. So, all silicon can be dissolved in the braze solid solution matrix phase without formation of silicides.
A narrow brazing gap produces similar results because of a small combined concentration of B and Si in the braze volume which becomes even lower after the B and Si diffusion in the BM. The result is a limited "B+Si" concentration in the joint for eutectic formation. Therefore, narrow gaps are strongly recommended to avoid the formation of intermetallic phases with B and Si.

- If the filler metal contains no boron then the amount of Si in it is usually enhanced to keep T_{Liq} low. The rate of Si diffusion in BM is relatively low; the silicides are formed in the joints even after an extended brazing time.
- Vast difference in the phase composition in the middle of joints (low B and Si amounts per the joint cross-section unit) and fillets always exists. This occurs because the volume of metalloids in fillets per joint cross-section is too large to be dissolved completely in BM over a “regular” brazing time. This causes fillets to be the usual locations where stress induced cracks originate in the vicinity of large intermetallic phases.
- The optimization of brazing time and temperature provides improvement not only of the phase composition and amount of intermetallic phases in the eutectic zone but also improves the morphology of chromium borides segregated at the BM grain boundaries. Such optimization yields a very substantial enhancement of the brazement mechanical properties [26].

3 Technological progress of brazing processing

3.1 BFM Forms and Placement

Amorphous BFM: It is not an exaggeration to attribute the appearance of rapidly solidified amorphous ductile BFMs as the major step forward in the development of high temperature brazing technology over the last 40 years [10, 27].

Indeed, most of BFM with metalloids are inherently brittle in the conventional crystalline form and cannot be produced in continuous shapes such as foil, wire, etc. Therefore, they were available only as powders or their derivatives. Starting from Sexton’s and DeCristofaro’s [10] discovery of RS potential in manufacturing of flexible amorphous brazing foil, this new class of filler metals has found numerous applications during the last three decades. These amorphous filler metals are known as METGLAS® Brazing Foil (MBF) alloys. Today, they are essential components of the AWS American Standard BFM Classification. Their total annual market sales come close to a quarter of all total sales of all Ni/B/Si-based alloys.

The most important advantage of RS amorphous and microcrystalline FM alloys is their flexibility and ductility. Because a ductile amorphous alloy brazing foil such as MBF may be used as a preplaced preform, there is no need for large brazing gaps, as those required with pastes, to achieve a complete filling of the braze cross section. MBF has a particular advantage over powder, and polymer-bonded tape forms because of its superior flow characteristics [28].

Gas-atomized powder has a very large total surface area with subsequently large amounts of surface oxides. These oxides prevent, to a certain degree, fusion of individual powder particles into a uniform liquid pool. The MBF flows more freely upon melting than any powder form. A smaller clearance associated with the amorphous foils also promotes improved retention of base metal (BM) properties because of curtailed BM erosion by the use of a smaller volume of FM in the MBF form. It also results in better joint microstructures with a smaller amount of detrimental eutectic phases because of narrower brazing gaps. It is easy to automate assembling of parts and MBF preforms and it consequently was without difficulty introduced into industrial production.

Powder placement via “silk screening” and “rolling” are recent attempts of industry to respond to challenges posed by MBF amorphous foil which may be used as preforms for covering large surfaces. New compositions were specifically developed for use in mass production of products such as heat exchangers (HE) [5, 6]. In the “silk screening” process a powder mixed with a binder is delivered through multiple openings of the mask screen and it deposited on profiled plate surfaces. The plates with the powder attached to some local spots are placed afterwards on each other and then brazed together. The multiple joints are formed in locations where there were contacts between powder covered spots. The rolling technique is also used to deposit powder mixed with binder on some protruding local points that should be brazed. Both processes can deliver an increased amount of the powder in brazing gaps. This leads to an increase of the cross-section of an each individual joint. As a result, the internal pressure that HEs can withstand can be increased. “Rolling” application also permits automation of powder deposition [29-31]. Both processes have been used on an industrial production scale but suffer from all the inherent deficiencies associated with powders.

3.2 Transient liquid phase (TLP) joining and joint loading during brazing

Both these methods can be considered together because both have the same goal- creating joints with composition as close as possible to that of base metals. More, a substantial joint loading is now applied with TLP in production of very large turbine parts working at high temperatures.

TLP joining has been attracting so much attention because it is applied in the manufacturing of critical and very expensive parts of modern aerospace and stationary turbines [32-34]. Its advancement is owed to a much better modern understanding of the brazing mechanism [21, 22, 35, and 36]. Various TLP models involving real multi phase alloys systems have been proposed in recent years [35, 36]. As a result, manufacturers are now provided with good heat treating instructions about how to carry out TLP and produce parts with excellent properties.

Out of many works related to TLP, the work of K. Nishimoto group, whose results were published in series of papers, should be particularly noted [37, 38]. The group studied the joining of separate single crystal superalloy parts into one single crystal that has the same crystal lattice orientation in both previously separate parts. They elucidated the effects of the BM and BFM compositions, and brazing temperature and time. Basic parameters of TLP kinetics were also determined and the process was described using a rather simple model. At the same time more sophisticated works were published describing real multiphase Ni-Al-B [21], Cr-B and Ni-Al-Cr-B [22], and other complex alloys [32].

Both experimental and theoretical works showed dramatic difference in the time needed for complete dissolution of the joint eutectic zone for different BFM. Such behavior depends directly on of the nature of melting point depressants such as boron and germanium, for example, from the diffusion mechanism point of view. Thus the time of complete eutectic dissolution in the case of the Ni/Cr-B MBF-80 vs.CMSX-2 superalloy at 1160 °C is 2.8 h [38]. On the other hand the dissolution time for Ni-23Ge/ReneN5 at about 1160 °C is at least in order of a magnitude longer [14] because germanium diffuses as a substitutional specie. Its diffusion rate is much lower than that of boron.

It is worth nothing that a thin preplaced Ni-15Cr-4B MBF-80 amorphous foil is used advantageously in number of cases involving TLP. Indeed, the foil preform covers the gap cross-section 100%; it is thin and thus contains a small amount of boron per the joint cross-section unit [33, 38]. Therefore, the filler metal can be completely dissolved in BM within a reasonable heat treating time [38].

Moderate loading, a few MPa, applied at a normal to the joint surface can strongly improve joint structure and mechanical properties. The appreciation of its positive effect on joint properties has been growing in the last years [18, 20, 39-41]. Loading is widely used in mass production of polycrystalline diamond bits, injectors of huge stationary turbine with brazed cross-section up 1 m^2 and jet turbine blades [20]. Today the hydraulic presses as elements of brazing furnaces supply load up to 1200 t (!) to large parts at about 1200°C. Another impressive example is brazing large gas pipes with wide brazing gaps [40]. Loading works well with 100% metal preforms covering the all gap cross-section. Therefore, BFM in the amorphous foil form are the best choice hereby. Explanation of the loading effect may be considered using "ejection model" [39]. The model relates the changes of joint structure due to mechanical rectification of BFM composition from a fraction of the liquid metal forming in the beginning of melting. As follows from the general phase diagram constitution, this fraction is always enriched in metalloids. The applied load ejects directly this compositional fraction. Therefore, the amount of intremetalllic phases in the crystallized joint decreases whereas the fraction of solid solution matrix phase increases. The loaded joints have a very beneficial microstructure consisting mostly from solid solution matrix phase. It was shown that moderate loading can increase the joint strength 100% and higher together with particularly large increase of the joint ductility [39, 41]. Very good and strong structures with very small amount of eutectic were obtained, for example, when using Ni/Zr/Hf alloys under 8-12 MPa load [18, 20].

4 Recent brazing application expansion

4.1 Brazing Repairs

One of the fast growing and important economically areas of application is repairing cracks which appear in blades and vanes of aircraft and stationary turbines during service [42]. The total direct sales associated with brazing repairs exceeds well a quarter of billion dollars. This application has the following specifics: brazing gaps have vastly different dimension along the crack length requiring high BFM flowability and wetting; the joint should have a structure similar to that of the BM parts and possess good mechanical properties. Traditional Ni/Cr-based alloys with B and Si as melting temperature depresants had been used for long [43-45] together with NiCr/Zr/Hf compositions. Ni-Zr/Hf alloys were specifically developed for and implemented in brazing repairs [18, 20, 46]. Recently, new Ni-Ge [14] and Ni-(20-60)Mn [47] BFM were successfully applied for repairing. The latter yield strong epitaxially crystallized joints due to aseotropic nature of Ni-Mn alloy system with unlimited mutual solubility of Ni with Mn in the solid state. The major advantage of Mn as a melting point depressant is its complete solubility in superalloys without formation of secondary intermetallic phases which appear in joints made of B- and Si-contaning BFM.

4.2 Three-dimensional brazed parts-heat exchangers and automotive engine components

The growing and urgent efforts to improve efficiency of the whole machinery producing and consuming energy in the world has resulted in explosive manufacturing expansion in many areas associated with energy conservation. Today brazing is thriving in production of 3-dimensional (3D) thin-walled honeycomb-like structures. The brazed joints,- sometimes thousand of them in one part,- are rather small and densely distributed in space on many levels. These remarkable, light-weight, temperature and corrosion resistant structures require a precise placement of thin preforms thus avoiding potential part erosion by molten BFM [48]. The list of applications with brazed energy-efficient 3D structures includes such products as heat exchangers, boilers, co-generators, heat recovery units, intercoolers, condensers in dryers, stationary jet turbines, fuel cells and many others.

The same intense efforts are now applied to pollution elimination and engine efficiency increase for cars, motorbikes and working vehicles in construction, mining, etc. Examples of these 3-D brazed structures are shown in Figure 1 [49].

Here five auxilary brazed units of a modern diesel engine are presented in a schematic way together with their photographs. These parts or units such as **M**etal **C**atalyst **S**ubstrates (MCS), **E**xhaust **G**as **R**ecirculator Coolers (EGRC), **O**il **C**oolers (OC), and **D**iesel **P**articulate **F**ilters (DPF), decrease the environmental impact of diesel and gas engines; they regulate the fuel/air gas mixture temperature and thus, increase their total efficiency.

Because a ductile amorphous alloy brazing foil such as MBF may be used as a preplaced preform, there is no need for large brazement gaps, as those used with powder pastes, to achieve a complete filling of the braze cross section. More, MBF, for example, have a particular advantage over powder, and polymer-bonded tape forms in 3D structures brazing because of its superior flow characteristics. The MBF flows more freely upon melting than any powder form [28]. A smaller clearance also promotes improved retention of BM properties because of curtailed BM erosion by the use of a smaller volume of FM in the MBF form. From the economical point of view, only about one half or even one third of the filler metal weight is needed per joint square area when using MBF as a filler metal vs. that of a sprayed or pasted powder. For all these reasons, a preplaced self-fluxing thin MBF preform is superior to the powder-containing paste in automotive applications shown in **Figure 1**.

5 Health Issues

There has been a substantial increase in production of brazed stainless steel plate/plate heat exchangers (HE) in the last 40 years. Many millions of HE units are manufactured using both copper and nickel-based BFMs. Conventionally manufactured HE units brazed with copper as a brazing filler metal have short service spans or fail entirely when exposed to conditions that exist in many modern HE utilizations. These utilizations include generation of hot water for heating and drinking application, and for synthesis of chemical and pharmaceutical products, etc. Today, there is a much greater awareness of the role that drinking water can play as one of the environmental factors affecting human health. Particular attention is now paid to the heavy metal content of the drinking water and food stuffs.

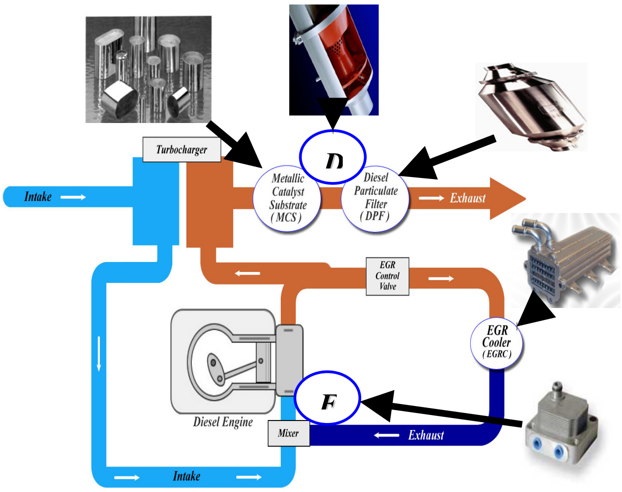

Fig. 1 Schematic of a modern diesel engine equipped with brazed parts that clean exhaust gas and increase engine efficiency.

The EU guidlines recently added nickel and its chemical compounds to the list of mildly hazardous substances. German Regulations DIN 50930-6 passed on June 2000 impose a maximum content of 20 µg/l of nickel in potable water flowing out of brazed heat exchangers. Furthermore, the regulationtory test procedure does not replicate conditions that exist in the actual HE deployment. The regulation recommends that Ni-based brazing filler metals should not be used for brazing of stainless steel HEs used for human drinckable water altogether. Meanwhile, our tests have shown that HEs brazed with both Cu- and Ni-base BFMs leach a noticable amount of Ni under certain conditions. No HE brazing solution has been discovered to date that meets both technical and economic limitations. No clear path has been mapped out showing how to proceed forward in attaining compliance with the Ni limiting HE regulation. As a way forward, a particular solution that utilizes a simple and inexpensive passivating treatment has been recently proposed in [50]. This passivation treatment can be achieved easily via keeping brazed HE for some time at 400 – 500°C in open air. Thus no change in the BMF composition is required. This heat treating proceedure achieves not only a substantial decrease in Ni-leaching in HEs but also decreases water ionic conductity to very low values

6 Conclusion

It seems miraculous that brazing, one of the oldest technologies developed by mankind is undergoing substantial advancements today. This progress is due to the unbeatable efficiency of brazing in joining sometimes very different multiple parts into a single and structurally integrated product. Indeed, brazing is utilized again and again as a key technology in the production of many new products. An additional reason for the ongoing technological progress is the activity of a small, devoted, and very knowledgeable world community of professional engineers and scientists working to advance brazing. The regular meetings of IBSC in the US and LOT in Germany - including the current LOT2010 - exemplify the innovative activities of our brazing community. Robert L. Peaslee made far-reaching contributions to brazing technology during more than 60 years of his career. These contributions exemplify his pioneering spirit of brazing innovation and will never be forgotten.

7 Literature

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