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Chongdo Park and Taekyun HaBoklae Cho

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Chongdo Park and Taekyun Ha
Pohang Accelerator Laboratory, 80 Jigok-Ro 127 Beon-Gil, Pohang, Gyeongbuk 37673, Korea
Boklae Cho
Korea Research Institute of Standards and Science, 267 Gajeong-Ro, Yuseong-Gu, Daejeon 34113, Korea

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Outgassing rates of three low-carbon steels were measured using rate-of-rise and throughput methods. Outgassing rates of water vapor during pump-down were higher than those of stainless steels, probably due to the nature of native surface oxide layer. However, hydrogen outgassing rates without a high temperature pretreatment were as low as $(1-4) \times 10^{-10} \text{Pa m}^3 \text{s}^{-1} \text{m}^{-2}$, which is much lower than that of untreated stainless steels. No dramatic reduction was observed in $H_2$ outgassing after vacuum annealing at $850 \degree C$ for 12 h, suggesting that the low-carbon steels had been fully degassed during the steelmaking processes. This may be due to the use of the Ruhrstahl-Hausen vacuum process during steel refining instead of an older process, such as argon-oxygen decarburization. The extremely low $H_2$ outgassing rate from low-carbon steels makes them applicable for use in ultrahigh vacuum or even extreme high vacuum applications, particularly where magnetic field shielding is needed. © 2015 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution 3.0 Unported License. [http://dx.doi.org/10.1116/1.4936840]

I. INTRODUCTION

Low-carbon steel (C $\leq 0.2$ wt. %) is a soft magnetic material that is relatively inexpensive and has a high magnetic permeability; it is widely used to shield sensitive experimental apparatus from stray magnetic fields. Low-carbon steel is often used as chamber material in vacuum devices when the required vacuum is not strict. In this case, low-carbon vacuum chambers are usually nickel-plated to prevent further corrosion and to improve the vacuum quality. For example, in electron microscopes, nickel-plated low-carbon steel is often used to construct the specimen vacuum chambers. This specimen chamber also prevents permeation by stray magnetic fields that may deflect the electron beam and thereby degrade the image.

Unlike the specimen chamber in which the pressure is in a high vacuum range, the electron gun of a high-resolution electron microscope requires ultrahigh vacuum (UHV) operation, so the gun chamber is normally made of stainless steel (STS). Permalloy and mu-metal are normally used for magnetic shielding in UHV, but the high cost of raw material and manufacturing hinders their widespread use for constructing UHV chambers. Permalloy or mu-metal is usually used in the form of a thin sheet inside an STS UHV chamber when the experimental apparatus should be shielded from stray magnetic fields.

To the best of authors’ knowledge, low-carbon steels have not been used in UHV systems, because the steels’ outgassing rates ($10^{-5}-10^{-6} \text{Pa m}^3 \text{s}^{-1} \text{m}^{-2}$ or higher) during pump-down are very high compared to those of STS ($10^{-8} \text{ Pa m}^3 \text{s}^{-1} \text{m}^{-2}$) after 10h of pumping. The hydrogen outgassing rates of a mild steel (carbon concentration $\sim 0.15\%$) and a chromium-plated mild steel were $2.6 \times 10^{-8}$ and $8 \times 10^{-8} \text{ Pa m}^3 \text{s}^{-1} \text{m}^{-2}$, respectively, after baking at $300 \degree C$ for $3 \text{h}$, whereas the outgassing rates of UHV chambers made of STS are normally $\sim 10^{-9} \text{Pa m}^3 \text{s}^{-1} \text{m}^{-2}$ after baking at $100–200 \degree C$.

However, if the outgassing rate of the low-carbon steels could be reduced sufficiently or if the outgassing rate is much lower than the values in the literature referenced, then these steels could replace the expensive mu-metal/STS combination as materials for construction of UHV chambers. However, information about how low-carbon steels respond to vacuum is sparse in the literature, so this information should be obtained systematically. In this study, the hydrogen and water outgassing rates of three commercially available low-carbon steels were tested before and after high-temperature pretreatment to reduce the outgassing. The ultimate pressures obtainable in vacuum chambers made of the steel were also quantified.

II. EXPERIMENT

The chambers were made from three low-carbon steels (carbon concentration 0.1%-0.2%, Table I) that are available in Korea. They are recommended for use in machine structures (D3752), ordinary piping (D3507), and pipes for pressure service (D3562).

These three steels, and a type 304 STS (for comparison), were tested as cylindrical chambers. D3752 steel was machined from a round bar into a bored cylinder with an inner diameter of 13 cm; D3507 and D3562 were cut as sections from pipes. All chambers were 46 cm long. To supply sufficient magnetic shielding, the wall of D3752 was 10 mm thick, which is much thicker than in usual STS chambers; the walls of D3507 and D3562 were 5 mm thick, and that of the type 304 STS was 3.3 mm. The cylinders were closed by welding circular machined plates of the same material onto both ends. Small ConFlat flanges (CF35) were machined on...
both end plates. In all cylinders, the area of the inner surface was \( \sim 2400 \text{ cm}^2 \), and the volume was \( \sim 71 \). All parts were degreased using detergents, rinsed with deionized water, welded, and helium leak checked before the tests.

The outgassing rate was quantified using the rate-of-rise (RoR) method. The method is suitable when the pressure increases linearly with time over a long period, as generally occurs during \( \text{H}_2 \) outgassing from an STS vacuum chamber after bakeout. An outgassing rate that is constant over a long period suggests that readsorption is negligible.\(^6\) Thus, we can measure the intrinsic \( \text{H}_2 \) outgassing rate \( q = (V/A)(dP/ dt) \), where \( V \) is the volume of the test chamber, \( A \) is the geometrical surface area of the chamber, and \( dP/dt \) is the measured rate of pressure rise in a sealed-off sample chamber at a constant room temperature with no pumping.

Before the RoR measurements, the sample chambers were baked at 150 °C for 48 h to remove adsorbed water molecules from the inner wall. A residual gas analyzer (RGA) installed on the roughing side was used to identify the residual gases emitted from the sample chambers; the dominant gas was \( \text{H}_2 \) after \textit{in situ} bakeout. Then, a spinning rotor gauge (SRG) was used to measure the pressure rise in each chamber for \( \geq 48 \text{ h} \). For all steels tested, the rate of pressure increase was constant, and so use of RoR to measure \( \text{H}_2 \) outgassing rate was valid.

The throughput method was used to evaluate outgassing during pump-down. Because the water vapor is mostly desorbed from the surface of the inner wall of a chamber during the initial stage of pumping, the method is optimized to measure the water vapor outgassing rate \( q = (C/A)\Delta P \), where \( C = 0.821 \text{ s}^{-1} \) (\( \text{N}_2 \) equivalent) is the conductance of the orifice and \( \Delta P \) is the pressure difference across the orifice. The orifice diameter was 3 mm. Because the pump-down curves in a vacuum system depend significantly on environmental conditions (e.g., humidity and duration of exposure) before pumping, every sample chamber was baked out \textit{in situ} at 150 °C for 48 h, then exposed to \( \text{N}_2 \) gas for 5 h before the measurements.

For measurements, the steel chambers were placed in an oven (for RoR) or an ordinary room (for throughput measurements) (Fig. 1). For the RoR measurement, an SRG was used to prevent errors caused by either pumping or the outgassing action of an ion gauge. Because temperature control is extremely important during operation of the SRG to ensure precise measurements of extremely low outgassing rates, an oven with active temperature control unit that consisted of a cooling coil at constant temperature of 15 °C and a proportional-integral-derivative controlled heater was used to maintain the temperature at 24 ± 0.1 °C. Throughput measurements were conducted in a room with the temperature actively controlled within ±1 °C. To investigate the high temperature annealing effect, all measurements were repeated after the specimens had been heat-treated at 850 °C for 12 h in a vacuum furnace.

After the trials, the ultimate pressure in the thick low-carbon steel chambers was measured. They were mounted on a pumping system composed of a small STS ConFlat flange (CF35), a sputter-ion pump with a nominal pumping speed of 601 s\(^{-1} \), a nonevaporable getter (NEG) module (SAES getters, WP950) with a nominal pumping speed of 4301 s\(^{-1} \), and an all-metal right angle valve to isolate a roughing pump. The ultimate pressure of the pumping system itself had been measured as 1.4 × 10\(^{-9} \) Pa before installation of sample chambers. Pressure was measured using extractor ionization gauges (IE514, Leybold).

III. RESULTS AND DISCUSSION
A. Hydrogen outgassing rate after \textit{in situ} bakeout

Most of the gas released was \( \text{H}_2 \) (Fig. 2); the measured rates (Table II) were all much smaller than the reference

![Fig. 1. Schematic of the experimental configuration for measuring the outgassing rate by RoR of the test chambers. For throughput measurements, a room instead of an oven was used with an orifice (diameter = 3 mm) between the sample chamber and pumping chamber. The orifice was detached for the base pressure measurements. Extractor gauges (IE514, Leybold), one in the SRG location and one after the orifice, were used to measure the pressure differences during pump-down.](image-url)
values for mild steels and ferritic steels. The measured outgassing rate for untreated STS304 (sample 6) lies in the typical range of reported; this similarity suggests that our measurements are reasonable.\(^5\)\(^7\)\(^8\)\(^9\)\(^10\)

The outgassing rates before pretreatment at 850°C were as low as \(\sim (1-4) \times 10^{-10}\) Pa m\(^3\) s\(^-1\) m\(^{-2}\), which are among the lowest reported for mild steels and materials used for magnetic field shielding (Table II).\(^5\)\(^11\)\(^12\) They were generally more than 2 orders of magnitude lower than values reported previously for untreated mild steels and ferritic steels, and slightly lower than that of copper-plated (100 μm) mild steel.\(^15\) The outgassing rates were lower than that of untreated STSs by a factor of \(\sim 10-50\) and were close to the values of outgassing of STSs after intensive heat treatment.\(^9\)\(^10\)\(^14\)\(^15\)

These differences may be due to difference in the steel-production processes, in particular, the secondary metallurgy during which impurities are removed.\(^16\)\(^17\) The reference values (Table II) for mild steels were published in the early 1970s. During that period, decarburization during steelmaking was generally done by mixed gas refining [e.g., argon-oxygen decarburization (AOD)] at atmospheric pressure, which is the most successful commercial ladle metallurgy. Vacuum degassing processes were developed for carbon steels during the late 1950s, and first used in a commercial plant in 1957,\(^16\)\(^17\) but in the early 1970s, only \(\sim 10\)% of steels produced in Japan were made under vacuum degassing.\(^18\)

In contrast, the most common process that is currently used to produce modern carbon steel is the Ruhrstahl-Hausen (RH) process, which is a decarburization and dehydrogenization process that is conducted under a process vacuum of \(\sim 70\) Pa.\(^18\)\(^19\)\(^20\) This process greatly reduces the amount of hydrogen dissolved in the bulk material, typically to as low as 1 ppm by weight.\(^19\)\(^20\) Therefore, the difference in steelmaking process might be the origin of the differences (Table II) in H\(_2\) outgassing rates of the steels tested versus the steels to which they were compared.

Standard grades of STS (e.g., 304) are usually made differently than the steels tested. STS304 is produced by using an electric arc to melt scrap iron and to add alloying elements. The pressure is either one atmosphere during AOD\(^21\) or \(8-20\) kPa during vacuum-oxygen decarburization.\(^19\) Furthermore, alloying elements such as Cr and Ni likely trap hydrogen during steelmaking process because they have a strong hydrogen affinity.\(^17\)\(^22\) This is another plausible

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**TABLE II. Total outgassing rates (H\(_2\) equivalent) after bakeout, \(d\), thickness of the chamber.**

| Material         | Sample no. | \(d\) (mm) | Preheat treatment | In situ bakeout | \(q\) (Pa m\(^3\) s\(^{-1}\) m\(^{-2}\)) | Comments |
|------------------|------------|------------|------------------|----------------|-------------------------------|----------|
| D3752 1          | 10         |            | 150°C, 48 h      | 2.6 \times 10^{-10} |                               |          |
| D3507 3          | 5          |            | 150°C, 48 h      | 8.8 \times 10^{-11} |                               |          |
| D3562 4          | 5          |            | 150°C, 48 h      | 6.3 \times 10^{-11} |                               |          |
| STS304 6         | 3.3        |            | 150°C, 48 h      | 6.2 \times 10^{-11} |                               |          |
| S15C             | 10         |            | 300°C, 3 h       | 4.1 \times 10^{-10} |                               |          |
| S25C             | 10         |            | 300°C, 3 h       | 6.8 \times 10^{-11} |                               |          |
| Mild steel       |            |            | 150°C, 48 h      | 1.4 \times 10^{-10} |                               |          |
| Permalloy (Ni-Fe-Mo-Cu) | 0.2      |            | 150°C, 48 h      | 7.8 \times 10^{-11} |                               |          |
| SUS430 (Fe-Cr)   | 3          |            | 150°C, 48 h      | 1.0 \times 10^{-10} |                               |          |

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\(a\) After the first measurement, chamber #1 was disassembled to remove 2 mm from the inner surface by machining, and then honed. Then, the chamber was rewelded and tested to determine the surface effect on the water outgassing characteristics (Sec. III B).

\(b\) Measured using throughput method.

\(c\) Method unknown. All other rates measured by RoR.
An explanation of why STSs (without high-temperature pretreatment) have higher H₂ outgassing rates than low-carbon steels.

Residual hydrogen contents measured using the extraction melting technique also strongly support our discussion. Four samples (4 × 8 × 3 mm) of each type were tested using LECO Hydrogen Determinator (RH 600, range 0.01–5000 ppm). As expected, H₂ content (wt. %) was very low in as-received low-carbon steel sample 1 (0.048 ppm) and sample 3 (0.17 ppm), but high in STS304 (sample 6) (1.64 ppm).

The reduction behavior of outgassing rates after pretreatment at a high temperature differed greatly between STS and the tested steels. To exploit the benefits of removing hydrogen dissolved in the bulk materials, we annealed the steels at 850 °C for 12 h. The outgassing rate for the low-carbon steel D3752 decreased by ~66% after heat treatment at 850 °C for 12 h in vacuum (Table II, sample 1). No meaningful reduction was measured even after a second consecutive heat treatment. Similarly, small reductions were observed for the low-carbon steel, D3507 (sample 3) and D3562 (samples 4 and 5). These reductions were very small compared to those observed after vacuum firing of STSs, which usually reduces the outgassing rate by more than 2 orders of magnitude.

The expected effectiveness of the heat treatment is often expressed as the dimensionless ratio \( F_0 \) of the treatment time to the characteristic diffusion time. At 850 °C, the diffusion constant for hydrogen in low-carbon steel is approximately \( 1 \times 10^{-4} \text{ cm}^2 \text{ s}^{-1} \), and heating a 1-cm-thick chamber for 12 h gives \( F_0 = 17 \); this implies reduction in \( \text{e}^{-17} \) (i.e., \( \sim 10^{-8} \)) in outgassing rate. The expected reduction suggests that H₂ outgassing from the low-carbon steels tested in this study might have been governed by a mechanism other than bulk diffusion, such as hydrogen "deep traps." Therefore, the very low H₂ outgassing rates of untreated low-carbon steels may occur because the bulk material contained very little dissolved hydrogen, i.e., mobile hydrogen atoms were fully degassed during manufacturing of the steels, which probably included a vacuum degassing step, such as the RH process.

### B. Outgassing rate during pump-down

Outgassing rates over time were measured during pump-down before (Fig. 3) and after vacuum annealing at 850 °C for 12 h (Fig. 4). The RGA confirmed that most of the desorbed molecules were water from the metal surfaces. The RGA spectra obtained from the steels showed no noticeable differences in residual gas compositions compared with ordinary vacuum chambers made of STSs (Fig. 5). Because the measured outgassing rates decrease according to a power law, \( q = q_0 t_n^{-a} \), where \( i \) is time, the measurements (Table III) are presented as \( q_i = q_0 t_n^{-a} \) to simplify comparison with the published values.

Outgassing rates of steel chambers after in situ bakeout (150 °C; 48 h) (Figs. 3(a) and 3(b)) were 20–30 times larger than the typical values of the untreated STS vacuum chamber (Fig. 3(d)). As an example, low-carbon steel D3562 (Table III, sample 5) had \( q_{10} = 9.4 \times 10^{-7} \text{ Pa m}^3 \text{ s}^{-1} \text{ m}^{-2} \) and followed the power law as \( 1.1 \times 10^{-5} t^{-1.09} \text{ Pa m}^3 \text{ s}^{-1} \text{ m}^{-2} (10 \leq t \leq 40 \text{ h}) \), whereas STS304 had \( q_{10} = 3.0 \times 10^{-8} \text{ Pa m}^3 \text{ s}^{-1} \text{ m}^{-2} \) and followed \( 3.0 \times 10^{-7} t^{-0.95} \text{ Pa m}^3 \text{ s}^{-1} \text{ m}^{-2} \) (Table III, sample 6). For the machined low-carbon steel chamber, the outgassing rate [Fig. 3(c)] was only three times larger than that of the STS vacuum chamber [Fig. 3(d)]. The measured pump-down curves show the typical surface desorption behavior (\( a \sim 1 \)) of water vapor diffusing through a surface oxide layer.

The outgassing rate of D3752 (sample 1) during pump-down was not measured in the beginning of our tests. Because the chamber had been already exposed to 850 °C during the first heat treatment, we disassembled the chamber, machined 2 mm of steel off the inner surface, and then honed the surface to recover its original state. Then, the chamber was rewelded and the outgassing rate during pump-down was tested again.

Outgassing rates after in situ bakeout were much lower than published rates for mild steels that had not been pretreated at a high temperature, i.e., \( q_{10} \) measured in this study were only \( \sim 1/3000 \) to \( 1/25 \) times those of the references listed in Table III. Because the outgassing rate depends strongly on the moisture content in the venting gas and the
Experimental conditions of reference data in Table III are mostly unknown, the comparisons should be general, rather than one-to-one comparisons.

Because all reference values in Table III were published in 1960s or 1970s, the large values seem to be related to the steel manufacturing processes that were used at that time. General structural steels at that time were usually contaminated with C, P, and S.36 Carbon steels emit CO gas continuously due to such processing technology.36 Because of this characteristic, the material has long been recommended only for use in applications for vacuum pressures ≥10⁻⁴ Pa.

A previous study37 obtained results similar to ours. The short-term (<100 h) outgassing rates from clean carbon steel were only two to four times larger than from similarly prepared STSs, and the authors noted that the increased outgassing rate appeared to be directly proportional to the thickness of the native oxide layer. Because steels usually have a thicker natural oxide layer than do STSs, the outgassing rates of the steels are higher than that of STSs. This may be a reasonable conclusion, because during manufacturing and storage, the steel surfaces are prone to corrode more severely than STS, in which chromium prevents further oxidation.

Surface roughness can also affect water outgassing because an increase in effective surface area can increase the number of potential water adsorption sites.9,34,38 The measured surface roughnesses Rₐ of the pipes were 2–2.5 μm and those of machined steel were 0.5 μm after machining and honing. Outgassing of the chambers made from pipes were higher than that of the machined steel chamber (Fig. 3, Table III), i.e., under consistent experimental conditions, the outgassing rate of water increases with Rₐ.

Pretreatment at high temperature in vacuum reduced water outgassing more than it reduced hydrogen outgassing rate (Fig. 4). Rates were all in the range of 10⁻⁸ Pa m³ s⁻¹ m⁻² at 10 h after evacuation (Table III). The outgassing rate for the chambers {D3507 [Fig. 4(a)] and D3562 [Fig. 4(b)]} that had been heat treated at 850°C for 12 h in vacuum was decreased by a factor of ~10 and approached the typical value of the untreated STS chamber (Fig. 3(d)). In the machined steel (D3752), the outgassing rate [Fig. 4(c)] became nearly the same as that of STS. Similar results were observed after degassing at 400°C for 15 h,32 and in STS 316 L, the rate decreased to about 1/5 of the original rate after degassing at 450°C in vacuum for 48 h.9

The values in Table III were measured using the throughput method during pump-down at room temperature. Outgassing rates are these values divided by air evacuation time (10 h). The values are N₂ equivalents of which the main component is water. All sample chambers were subjected to in situ bakeout for 48 h at 150°C and subsequent N₂ gas exposure for 5 h before the measurements.

| Material | Sample no. | q₀ | q₁₀ | q₂₄ | q₀ t₀⁻⁴ or a₀ (10–40 h) | Remarks |
|----------|------------|----|-----|-----|-------------------------|---------|
| D3752    | 1          | 4.5 × 10⁻⁷ | 4.3 × 10⁻⁸ | 1.7 × 10⁻⁸ | 5.0 × 10⁻⁷ t⁻¹.⁰⁵ | After degas (850°C, 12 h) |
|          |            | 1.2 × 10⁻⁶ | 9.9 × 10⁻⁸ | 4.0 × 10⁻⁸ | 9.7 × 10⁻⁷ t⁻¹.⁰⁰ | After machining by 2 mm and finished using honing |
| D3507    | 3          | 4.6 × 10⁻⁷ | 3.9 × 10⁻⁸ | 1.8 × 10⁻⁸ | 3.3 × 10⁻⁷ t⁻⁰.⁹¹ | After degas (850°C, 12 h) |
|          |            | 1.0 × 10⁻⁵ | 7.1 × 10⁻⁸ | 2.9 × 10⁻⁸ | 6.6 × 10⁻⁶ t⁻⁰.⁹⁸ | |
| D3562    | 4          | 9.5 × 10⁻⁷ | 7.1 × 10⁻⁸ | 3.0 × 10⁻⁸ | 6.6 × 10⁻⁶ t⁻⁰.⁹⁷ | After degas (850°C, 12 h) |
|          | 5          | 8.7 × 10⁻⁷ | 8.2 × 10⁻⁸ | 3.7 × 10⁻⁸ | 6.7 × 10⁻⁶ t⁻⁰.⁹² | After degas (850°C, 12 h) |
| STS304   | 6          | 7.2 × 10⁻⁷ | 6.3 × 10⁻⁸ | 2.8 × 10⁻⁸ | 5.5 × 10⁻⁷ t⁻¹.⁰⁴ | After degas (850°C, 12 h) |
| Mild steel | —         | 5.6 × 10⁻⁴ | 1.8 × 10⁻⁵ | 1.8 × 10⁻⁵ | a₁₀ = 1 | Ref. 31 |
| Mild steel | —         | 2.7 × 10⁻³ | 2.7 × 10⁻⁴ | 4.0 × 10⁻⁵ | Ref. 11 |
| Mild steel | —         | 6.7 × 10⁻⁴ | 6.7 × 10⁻⁵ | 6.7 × 10⁻⁵ | Ref. 2 |
| Mild steel | —         | 2.5 × 10⁻⁶ | 5.3 × 10⁻⁷ (100 h) | Ref. 32 |
| Mild steel | —         | 1.6 × 10⁻⁵ | — | — | Ref. 32 |
| S15C     | —          | ~2.6 × 10⁻⁶ | — | — | Degassed, 400°C, 15 h |
|          | —          | 300°C, 3 h bake + air vent + (1–38 h) exposure | | | |
The native oxide layer at the surface of steels decomposes at such high temperature in vacuum. At the same time, the quantities of surface impurities, especially carbon, are reduced to an extremely low level. The oxide layer is believed to be cleaner and smoother than layers that had not been exposed to high temperature heat treatment as in the stainless steel, although further study is necessary to evaluate this possibility. The former surface in turn has fewer adsorption sites for water than does the latter.

C. Base pressure of low-carbon steel chambers

Ultimate vacuum pressure in chambers made of low-carbon steels was investigated to confirm the benefit of this work for real-world applications, for example, electron microscopes and accelerators. In such applications, pumping is usually done using rather small ports, and so in this study, the pumping was done through CF35 flange that has a pumping speed for H₂ of ~128 l s⁻¹.

Ultimate pressures of the low-carbon steel chamber [D3507, sample 2 (Fig. 6(a))] and the STS304 chamber [sample 6 (Fig. 6(b))] were obtained after pumping for 24 h followed by baking at 150 °C for 48 h. At the end of baking, a NEG pump was activated at 450 °C for 1 h. The ultimate pressure in the steel chamber installed on the NEG/SIP pumping system was 2.3 × 10⁻⁹ Pa and that in the same-sized STS chamber was 1.2 × 10⁻⁸ Pa. The results clearly show the benefit of using low-carbon steels to obtain UHV.

The result is even more beneficial for a system that is baked for a short time, i.e., D3562 (sample 5), which was baked for 2 h with NEG activated for the last 1 h. Use of this steel in combination with the NEG/SIP pump achieved UHV <1 × 10⁻⁸ Pa in only 6 h [Fig. 6(c)]. The pressure after 24 h from the start of evacuation was 3.9 × 10⁻⁹ Pa. This marked result may be attributed to the combination of low outgassing by the steels and fast water and hydrogen removal by the NEG, which are effective to compensate for the low conductance of the pumping port. This is a valuable result because rapid pumping to UHV with short and low-temperature baking is attractive in applications in which magnetic properties and baking are concerns.

The very low outgassing rates of low-carbon steels make their use feasible for applications such as magnetic field shielding in electron microscopes; protection of electron beams from external magnetic fields in accelerators; and construction of XHV systems. In these applications, use of low-outgassing low-carbon steels could eliminate the need to coat the inner surface of the material with protective film. However, the steels need appropriate surface coating on the air side, for example, Ni-plating or Teflon coating with which a continuous in situ bakeout is possible up to 250 °C. When these steels are used, the inside of the steel chamber should be kept in vacuum, because the steel is susceptible to oxidation during contact with ambient air, and oxidation must be avoided.

IV. SUMMARY

We examined the outgassing rates of three low-carbon steels in vacuum to evaluate the feasibility of using them as materials for ultrahigh vacuum systems. This is the first investigation of bare, low-carbon steel chambers for use in UHV systems subjected to heat treatments. The results are summarized as follows:

1. Low-carbon steels that had not received a high temperature pretreatment presented very low hydrogen outgassing rates, ~(1–4) × 10⁻¹⁰ Pa m³ s⁻¹ m⁻², which is ~1/50–1/10 times that of ordinary STSs.

2. Intensive preheat treatment for 12 h in vacuum at 850 °C, which is a typical demagnetization temperature, did not reduce hydrogen outgassing significantly.

3. Results suggest that most mobile H₂ is degassed during the steel making process, in particular, during secondary metallurgy such as the Ruhrstahl-Hausen process, and thus, bulk diffusion no longer governs desorption phenomena in the low-carbon steels tested.

4. The outgassing during pump-down from low-carbon steel chambers was about 3–30 times larger than the typical values of untreated STSs. However, annealing at high temperature in vacuum is effective to reduce water outgassing during pump-down. The phenomenon seems to be related to the nature and thickness of the native surface oxide layer.

5. Because the outgassing is low enough, plating inside the vacuum chamber might not be necessary to improve vacuum quality.

In conclusion, the hydrogen outgassing rates of low-carbon steels tested in this study were very low after simple chemical cleaning. These materials are beneficial for applications in magnetic-sensitive UHV systems in accelerators or electron microscopes.

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