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Powstańców Warszawy 8, 35-959 Rzeszów (e-mail: phyeco@prz.edu.pl)
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Violetta BEDNARSKA[1]
Henryka CZYŻ[2]
Tadeusz JASIŃSKI [3]

ADVANCES IN HEARING PROSTHETICS

This text analyses several topics connected with hearing test methods and hearing prosthetics for patients with hearing impairments or hearing loss. The hearing is one of the senses which plays a crucial part in human's cognition of the surrounding world and spatial orientation. Proper functioning of the hearing organ is a foundation of communication between people as well as the development of civil society. A hearing impairment or hearing loss disrupts social relationships between people, it entails developmental disorders in children, and causes learning difficulties. Methods of diagnosing patients and hearing prosthetics are very complex topics and are investigated by interdisciplinary research teams. The development of these fields of medicine and technology contributes to improving the quality of life for people with hearing impairment or deafness. This paper presents ways and means of improving or compensating for hearing losses with the use of hearing aids. Nowadays, hearing impairments and hearing losses concern even young people. One of the reasons for the deterioration of hearing is the ubiquitous noise in the modern world. Moreover, this text discusses the construction of hearing aids, with a particular emphasis placed on modern technological solutions. It is highlighted that hearing aids are currently available for the general public.

Keywords: auditory perception, hearing test methods, hearing aids

1. INTRODUCTION

Hearing is one of the long-range senses. It is crucial in order for humans to be able to receive information about the external world, and to orientate themselves in space. The hearing organ receives stimuli without our conscious knowledge – it is even active when we are sleeping. The human ear is a system that detects the direction, volume, pitch and timbre of sound. A diagram of the construction of the human ear is shown in Fig. 1.

[1] Corresponding author: Violetta Bednarska, Rzeszow University of Technology, Powstańców Warszawy 12, 35-959 Rzeszów, e-mail: v.bednarska@prz.edu.pl
[2] Henryka Czyż, Rzeszow University of Technology, e-mail: hczyz@prz.edu.pl
[3] Tadeusz Jasiński, Rzeszow University of Technology, e-mail: jasinski@prz.edu.pl

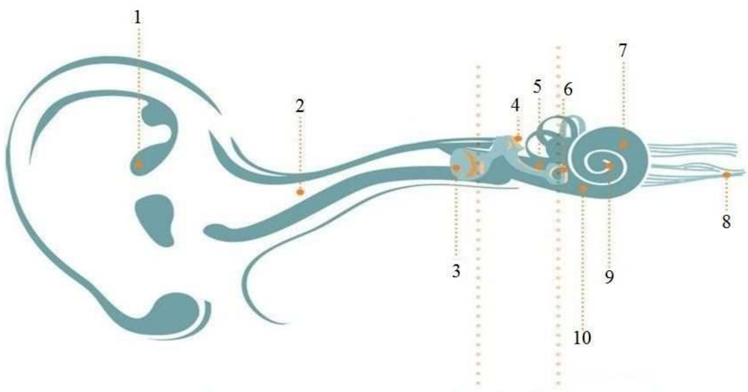

Fig. 1. The hearing organ. Outer ear: 1 – Pinna, 2 – Auditory Canal, 3 – Tympanic membrane. Middle ear: 4 – Malleus, 5 – Incus, 6 – Stapes. Inner ear: 7 – Cochlea, 8 – Cochlear nerve, 9 – Vestibule, 10 – Round window

Hearing is said to be the most important social sense. Its impairment or loss affects social interaction [1, 2].

Depending on the patient age, hearing loss may cause developmental deficits (in children) or learning difficulties, or may simply prevent the affected individual from functioning in a world where communication is based on sounds. Therefore, considerable attention is paid to hearing prosthetics which can restore hearing even to a large extent, depending on the degree of hearing loss and the applicable prosthetics.

Hearing disorders may be due to a variety of hearing defects. Consequently, the location of the hearing problem is a key element in choosing a suitable hearing aid.

Depending on whether interaction with the patient during a hearing test is necessary or not, the types of hearing tests can be divided into subjective (psychophysical) tests, in which the patient's active participation is essential, and objective (electrophysiological) tests, in which no active cooperation between the patient and the testing person is required [3].

2. SUBJECTIVE HEARING TESTS

2.1. Psychophysical tests

The most common subjective hearing tests include:

- speech audiometry,
- behavioural observation audiometry,
- pure tone audiometry [4].

Irrespective of the hearing test to be subsequently applied, the first diagnostic step should be to take the patient's medical history. It aims to identify the patient's problems, as well as the sound environment they live in and the level of hearing improvement they expect.

2.2. Speech audiometry – distance test

This test method is used to assess hearing acuity and hearing loss. Hearing acuity defines the greatest distance from which speech is clearly heard and exactly repeated by the patient. It is expressed in metres or centimetres.

Such a hearing test based on natural speech does not allow determination of the location of hearing loss in the auditory pathway; it only makes it possible to determine whether a given patient has a hearing problem [3].

Weber test

This test allows for a determination of the type of hearing loss - it makes it possible to determine whether the patient's hearing is asymmetric or symmetric (Table 1). Symmetric hearing means that the hearing loss is of the same type and degree in both ears. If sound is heard only in in one ear, then the patient hearing is asymmetric.

Table 1. Patient cases of hearing loss

Sound is heard everywhere in the head	Symmetric hearing
Sound is heard in the middle of the head	Symmetric hearing
Sound is heard on the left	Asymmetric hearing
Sound is heard on the right	Asymmetric hearing

Rinne test

The Rinne test is performed separately for each ear. Based on the length of time the patient can hear the tuning fork, it is possible to determine the type of hearing loss in the ear tested.

Schwabach test

The Schwabach test is based on comparing bone conduction in the patient and that in the examiner (with an assumption that the examiner has normal hearing). The test is performed separately for each ear. The type of hearing loss can be determined by comparing the lengths of time the patient and the examiner can hear the bone-conducted sound.

Bing test

This test is based on an assessment of the occlusion effect in an occluded ear. It is performed separately for each ear, with the use of tuning forks. It is used to test absolute and relative bone conduction of sound. If the result of this test is positive, then the patient's hearing is normal or there is sensorineural hearing loss in the ear tested. If the Bing test yields a negative result, then the patient's hearing loss is conductive hearing loss.

Lewis-Federici test

This test is performed using a tuning fork. If the test yields a physiological result, the patient has normal hearing or sensorineural hearing loss. If the test result is pathological, the patient has conductive hearing loss.

Gellé test

This test helps to confirm, in the case of a pathological result to the Lewis-Fereici test, that the patient has conductive hearing loss.

2.3. Audiometers

Audiometric tests are performed using an audiometer that generates auditory stimuli consisting of sine waves and noise [5].

An audiometer is a measuring device designed to evaluate hearing acuity using pure tone or speech signals. It is built of a system setting signal intensity, a signal generator producing tones and noise of different frequencies and volumes, air and bone conduction headphones and a loudspeaker emitting such signals. Audiometers can be broken down by the type of emitted signals, the type of signal presentation and by functions, hearing levels and frequencies.

The aim of an audiometric test is to determine the degree of hearing loss. Threshold tests are performed to determine the patient threshold of hearing. The audible thresholds are presented as a broken line in an audiogram. The line connects dots representing hearing levels for the particular frequencies expressed in dB HL (decibels Hearing Level).

Audiometric tests require a conscious response to auditory stimuli from the patient.

2.4. Methods for measuring auditory thresholds

Auditory threshold measurements for air and bone conduction differ due to the difference in the two conduction mechanisms. Supra-threshold tests are for the purpose of assessing the impact of supra-threshold stimuli (i.e. stimuli above 0 dB SL (decibels Sensation Level)) on the organ of hearing (Table 2).

Supra-threshold tests also allow the determination of the precise location of damage to the auditory pathway. There are four types of supra-threshold tests, namely:

- loudness compensation,
- intensity differentiation,
- adaptation and auditory fatigue,
- hearing in noise.

Intensity differentiation tests, adaptation tests, auditory fatigue tests and hearing in noise tests (HINTs) are also used to measure hearing loss.

Table 2. Sound assessment scale

Sound reception	Value [dB SL]
No sound heard	0
Very quiet	1 - 11
Quiet	11 - 20
Moderately loud (well heard)	21 - 30
Loud	31 - 40
Very loud	41 - 50
Too loud	> 50

3. OBJECTIVE HEARING TESTS

3.1. Impedance audiometry

Impedance audiometry is a simple, non-invasive and automated method for hearing assessment. The test takes no more than a few minutes. The test result is not influenced by the attitude of the patient or by their level of cooperation, so this method is very useful in measuring children's hearing. It is also the most widespread among apparatus-based methods, and the measuring devices used in this method are part of the basic equipment of every audiology room [6].

The parameter tested is the acoustic impedance of the middle ear. It is the resistance put up by the sound conduction system (tympanic membrane, three auditory ossicles and ligaments in the tympanic cavity) to acoustic waves. The most common impedance values for a normally hearing ear range between 1000 and 3000 acoustic ohms.

Most modern audiometric devices are based on the reciprocal of acoustic impedance, that is, acoustic admittance. Admittance can be defined as the ease of acoustic energy flow through the vibrating system of the middle ear. The unit of admittance is 1/ohm.

Tests using impedance audiometry help to detect various conditions of the middle ear and the state of the connections between its components.

Impedance audiometry refers to several tests which allow:

- calculation of the acoustic impedance value for the ear,
- testing of the motor function of the facial nerve,
- assessment of patency of the Eustachian tube,
- determination of the acoustic reflex threshold,
- differentiation between cochlear and retrocochlear hearing losses based on the stapedius reflex.

3.2. Tympanometry

Tympanometry is a measurement of pressure in the middle ear. The impedance of the middle ear is measured using the so-called impedance bridge [7]. In such a measurement, air pressure in the external auditory canal is changed from negative to positive and, at the same time, a test tone of a specific frequency is generated - this is the measurement of the system compliance. The compliance is the ability of the ear structures to stretch when exposed to various factors. Modern tympanometric devices automatically calculate the middle ear compliance [8]. The tympanometry result in the form of a tympanometric curve provides information about possible defects in the sound conduction system. Depending on the tympanogram type, the distinctive shape of the curve may, for example, indicate exudative otitis media, Eustachian tube dysfunctions or atrophic scars in the tympanic membrane etc. [8].

3.3. Stapedius reflex

The stapedius reflex, also known as the acoustic reflex, occurs in people with normal hearing and is absent in deaf people [9]. It is triggered by a high-intensity sound stimulus in the transversely striated muscles and is one of the bilateral reflexes (activation of one side with a strong stimulus triggers a binaural reflex). It is a defense reflex - it protects the inner ear against loud sounds and Corti's organ against damage.

The aim of the acoustic reflex test is to test the reflex and to determine the lowest intensity of an acoustic stimulus that will decrease the compliance of the middle ear. Absence of the reflex may indicate conductive or perceptive hearing loss.

3.4. Otoacoustic emission

The phenomenon of OAE (otoacoustic emission) was discovered in 1976 [10]. The emission is a reaction of auditory hair cells to a sound stimulus. When sounds are heard, the sensory cells of the cochlea act as an amplifier, contracting and relaxing. The cochlea is the place where an otoacoustic emission is generated. An echo comes from various cochlear processes and is associated with the contraction of the outer hair cells. When the sound heard is pleasing, the brain "orders" the cochlea to make it louder, and, in contrast, when the sound is received with reluctance, the cochlear has to make it softer. A part of the sound comes back to the ear. It can then be measured and the hearing quality can be assessed.

An otoacoustic emission is a faint sound generated from within the inner ear and emitted to the external auditory canal.

OAEs are among the objective and non-invasive methods for the assessment of the cochlear micromechanics. OAEs allow assessment of the inner ear function and detection of disturbances in sensory cells. This method is used to test for hyperacusis and to detect hearing losses caused by pharmaceutical agents. The phenomenon of otoacoustic emissions is present in all subjects, even in newborns.

Spontaneous otoacoustic emission (SOAE)

A spontaneous otoacoustic emission (SOAE) is a sound emitted from the ear spontaneously, without external acoustic stimulation. Its clinical application is limited. It is not observed in all subjects with normal hearing and is therefore not commonly used to diagnose hearing impairment.

Evoked otoacoustic emission (EOAE)

An evoked otoacoustic emission (EOAE) is one of the most valuable methods to test hearing. It is observed in all or almost all healthy ears. Such an emission is a response from the cochlea to an auditory stimulus emitted to the outer ear. We can distinguish between several types of EOAEs which differ in the stimulus produced.

Evoked otoacoustic emissions are used in a wide variety of clinical applications. With them it is possible to:

- perform screenings for potential hearing loss,
- monitor hearing impairments resulting from exposure to noise,
- monitor ototoxicity of drugs
- detect functional deafness
- diagnose tinnitus
- monitor the cochlear functions during neurootological operations.

Auditory evoked potentials

Auditory evoked potentials (AEPs) are of great importance in the diagnosis of hearing disorders [6]. These techniques measure an expression of the electrical activity in certain sections of the auditory pathway.

We can distinguish between potentials generated in:

- the cochlea,
- the vestibulocochlear nerve,
- the brain stem,
- subcortical centres and the cerebral cortex.

AEPs are critical in the diagnosis of hearing impairment in babies and newborns. They allow early detection of retrocochlear disorders and are used to assess hearing sensitivity, to make differential diagnostics and to intraoperatively monitor the electrical activity of the auditory system. The evoked potential method is shown schematically in Fig. 2.

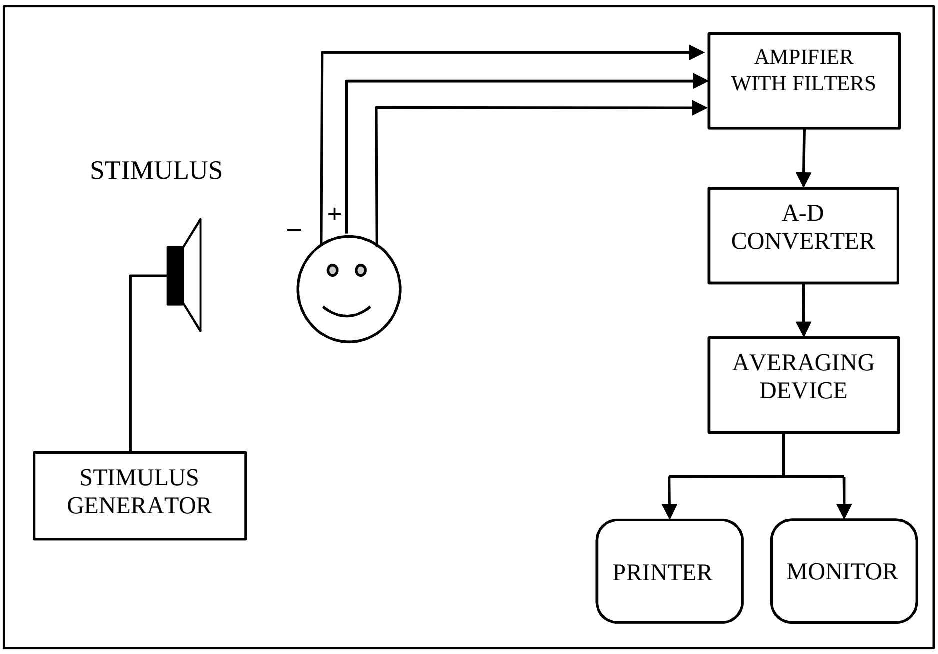

Fig. 2. The apparatus set used for recording auditory evoked potentials. +, - electrodes

3.5. Types of auditory evoked potentials

Electrocochleography

Electrocochleography (ECOG) is a hearing test which consists in measuring electrical potentials generated in the middle ear in response to sound stimulation. ECOG is not very useful in clinical practice because an electrode must be placed in the tympanic cavity or in the auditory canal. Electrocochleography is seen as an invasive method. It is applied only when auditory neuropathy or Ménière's disease is suspected.

Brainstem auditory evoked potentials

Brainstem auditory evoked potentials (BAEPs) are used to [8]:

- determine audible thresholds,
- perform screenings for potential hearing loss in newborns,
- perform differential diagnostics of hearing disorders,
- monitor the function of the brain stem and the vestibulocochlear nerve during otoneurosurgical procedures.

This test is performed to examine patients of all ages, including adults and babies.

BAEPs are often used to diagnose retrocochlear hearing disorders. In this test, response to a click is recorded separately for each ear and then the parameters are compared to each other and to normal ranges.

Middle latency responses (MLR)

MLR can be used to assess auditory thresholds, especially for low frequencies which are difficult to assess by other methods.

Mismatch negativity (MMN)

Auditory mismatch negativity (MMN), or long-latency auditory evoked potentials should be the cerebral cortex's automatic response involving detection of a lack of compliance between the features of the frequent stimulus and those of the rare stimulus. The MMN method can be applied in research on sound recognition and perception processes as well as in examinations of patients with disorders relating to the central process of auditory information processing.

Auditory steady state response (ASSR)

Auditory steady state response (ASSR) is linked to middle latency responses. ASSRs are analysed using modern statistical methods. The ASSR method can have applications in determining the auditory threshold in normally hearing and hearing-impaired individuals. The use of continuous stimuli makes it possible to record responses from both persons with hearing aids and those with cochlear implants. This allows an objective assessment of the effectiveness of the process of choosing hearing aids or implants for children.

4. CORE COMPONENTS AND CLASSIFICATION OF HEARING AIDS

4.1. Diagram of a hearing aid

A block diagram of a hearing aid [6] is shown in Figure 3.

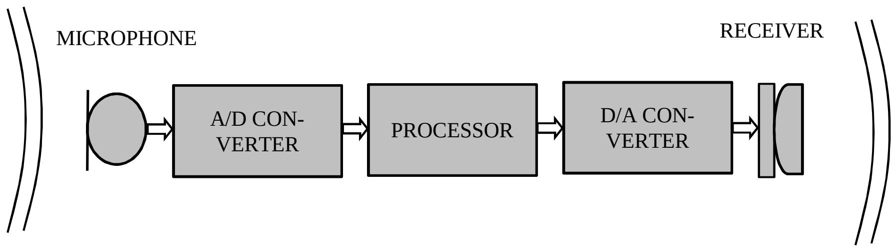

Fig. 3. A block diagram of the digital processing path in a hearing aid

Microphone

In hearing aids, the microphone is responsible for converting an acoustic signal into an electrical signal which is then processed by the hearing aid processing systems. The electrical signal must be as close as possible to the acoustic input signal of the hearing aid.

The use of several microphones in one hearing aid means that they must be miniaturized whilst maintaining similar acoustic parameters. The introduction of MEMS (microelectromechanical systems) technology enables construction of microphones with considerably smaller sizes than those existing to date.

Amplifiers

An amplifier is used to increase the value of the electrical signal from the microphone (accordingly for the particular frequency bands required and dependent on the patient's hearing loss). The amplifier makes the sound, the level of which is lower than the hearing-impaired individual threshold of hearing, audible to the individual.

Compression systems

Compression systems are used to limit the output signal of the hearing aid and to adjust the acoustic signal dynamics of the hearing aid microphone to the auditory dynamics of the hearing-impaired individual.

Filters

Hearing aid filters are systems that allow the shaping of the frequency characteristic in the hearing aid receiver.

Distinctions are made between:

- high-pass filters that allow higher signal amplification for higher frequencies,
- low-pass filters that allow ensuring higher amplification for lower frequencies,
- band-pass filters that pass components of the acoustic signal for a specific frequency range – between the lower and the upper cut-off frequencies,
- band-elimination filters that pass components of the acoustic signal which are present outside a specific frequency range [6].

Filters are applied in hearing aids for shaping the amplification characteristic within a wide frequency range. The frequency characteristic includes specific resonances - sudden signal escalations by even several decibels for narrow frequency bands. This has an adverse effect on the hearing aid's frequency characteristic. The main reason for these resonances to occur is, more than anything else, the system characterised by a specific resonance frequency dependent on the sizes of the said components.

The resonances make speech less clear, cause difficulty in identifying sounds and reduce the quality of the sound transmitted by the hearing aid. Variously shaped silencers, made from different materials, depending on the hearing aid parameters, are used to eliminate the resonances in the frequency characteristic.

Digital system

The digital technology applied in hearing aids allows them to more effectively process the acoustic signal because the digital signal processor:

- compresses and amplifies the signal (in accordance with the perception models for a given pathology and those for normal hearing),
- performs spatial filtering and reduces disturbing noises and acoustic feedback (separately for the useful signal and for the noisy signal), etc.

The system uses specialist algorithms responsible for storing specific setting parameters in the hearing aid (which depend on the degree and type of hearing loss and on the patient's perceptual habits). The settings are selected automatically in accordance with the acoustic conditions of a given environment [11].

4.2. Sampling and quantization

A process in which a discrete value is attributed to each and every value within the time of the signal amplitude component and in which a numerical quantity is attributed to discrete components is called signal quantization. This process is completed by an analog-to-digital converter (a/d converter). Quantization, sampling and processing of a digital-analog signal involves the risk of a specific error.

It is possible to minimize such errors by starting a series of procedures for the sampling, processing, and quantizing of the signal.

Speech signal components (vowels and consonants) are sensitive to quantization errors. Vowels are more sensitive than consonants. For vowels, an individual with normal hearing will notice differences in the auditory perception when the resolution of the converter is transformed by 3 bits, whereas for consonants, differences are noticeable when the resolution is changed by 10 bits. This is due to the easier detection of the disturbances occurring in the harmonic structure of vowels.

People with normal hearing demonstrated the same understanding of speech, when the signal was quantized with either an 8-bit converter or a 16-bit converter (an 8-bit converter is characterised by signal dynamics of 48 dB, whereas a 16-bit converter by dynamics of 96 dB). When using a hearing aid with a converter with a degree of quantization above 12 bits, they described the speech signal as "noisy". Typically, the use of analog-to-digital converters with a resolution above 8 bits guarantees that the reception of the quantization noise will fade out.

In digital hearing aids, the components that may contribute to delay distortions are the microphone and the receiver, both of which are analog components. Given their physico-material and geometric parameters, it can be speculated that the distortions caused by them are very slight.

Receivers

Most hearing aids feature an electromagnetic receiver. Its operating principle is identical with that of a dynamic loudspeaker: changes in the current flowing through the coil in the speaker cause changes in the magnetic field it generates. In turn a permanent magnet is inside this magnetic field connected to a membrane. The changing magnetic field causes it to move, setting the membrane in motion. The membrane forces air particles to move and the result is an acoustic wave.

In the hearing aid receiver, the membrane’s motion is made by a small circuit system that connects the variable magnetic field (generated by the coil) to the fixed magnetic field generated by the magnet.

Hearing aid receivers, just as hearing aid microphones, should feature a frequency characteristic that ensures good transmission of the “speech banana”. It is equally important that this characteristic is relatively flat and devoid of distinct extrema. The structure of the entire electromechanical system contributes to the occurrence of such extrema. The extrema are a result of magnetic resonance of the membrane and of resonance of the air inside the receiver. A lack of evenness in the frequency characteristic can be compensated by various solutions, such as acoustic and electric filters [6].

Powering hearing aids

Powering electronic hearing aids has always been, and still is, an important issue.. A hearing aid should work continuously and for as long as possible. This determines the necessary properties of the power supply. The hearing aid parameters should not vary over time. It is therefore necessary to use a stable source of energy. Electric cells, or batteries, have been used in hearing aids as a source of energy for many years. Today, electric cells enable operation of a hearing aid for as long as 2 weeks.

Accumulators are also used in hearing aids (mainly in first class devices) however they work for a considerably shorter time than batteries. The positive point of this solution is the possibility of making the hearing aid smaller. The negative points are the relatively high manufacturing cost of such an energy source, and its short working time after recharging. This solution therefore requires frequent access to an external electricity supply.

4.3. Classification of hearing aids

Hearing aids can be divided up into a number of types [12]. The simplest division is that according to their structure. It is directly associated with the device sizes.

- Pocket devices are the biggest hearing aids .
- Behind-the-ear (BTE) hearing aids are most popular.

Another group is made up of hearing aids inserted in the ear canal. All the hearing aid components are enclosed in the housing that is individually moulded to fit the patient ear.

- In-the-ear (ITE) hearing aids are custom-made to fit completely in the patient ear, i.e. in the concha (cavum and cymba).
- In-the-canal (ITC) hearing aids are smaller than in-the-ear hearing aids and are partly visible in the concha.
- Completely-in-the-canal (CIC) hearing aids are virtually invisible in the patient ear.

Hearing aids that are directly inserted in the patient ear canal are hardly visible and, compared to other hearing aid types, ensure the best location of sound sources (when inserted, the microphone is inside the external auditory canal). The drawbacks of such hearing aids are their high susceptibility to acoustic feedback (due to the short distance between the microphone and the receiver), exposure to dampness (a risk of damage to the hearing aid) and more difficult volume control (due to the small size).

An eyeglass hearing aid is a combination of hearing aids and glasses. The eyeglass rims have in-built BTE hearing aids [6].

5. MODERN TECHNOLOGICAL SOLUTIONS FOR HEARING AIDS

5.1. Elimination of acoustic feedback

The following non-exhaustive list of systems designed to prevent generation of redundant signals can be applied to reduce acoustic feedback [13]:

- tight ear moulds,
- reduction of amplification within the set frequency range in which the feedback arises,
- smaller ventilating holes in the ear mould or use of a closed ear mould,
- narrow-band filters (so-called notch filters).

Currently, the most effective feedback reduction system is one that uses the anaphase signal. The system monitors the hearing aid's output by detecting feedback with a distinctive frequency and generates a signal with the same amplitude and frequency but in opposite phase. This results in complete disappearance of the component responsible for the generation of acoustic feedback. The application of this system allows additional amplification of the signal by a few decibels.

5.2. Compression systems

Automatic gain control, or a compression system, is a system in which an increase in the input signal amplitude results in automatic reduction of amplification of the hearing aid's output signal.

There are two basic types of compression system:

- on-input compression system (AGC_1) which adjusts the dynamics of the acoustic input signal of the hearing aid to the dynamics of the field of hearing remnants in the hearing-impaired individual,
- on-output compression system (AGC_0) which reduces the pressure level of the output signal of the hearing aid.

Hearing aids should be fit to the individual and their settings should be later corrected so as to meet the patient needs which may depend on the acoustic environment they live in. This is facilitated by the following systems: Datalogging, and Ddatalearning.

Datalogging, datalearning

The Ddatalearning and datalogging functions are used in a number of hearing aid types by different manufacturers [3].

The data storage function, or datalogging, stores the data containing the hearing aid user's preferences during everyday use, such as:

- the length of time of remaining in an acoustic environment,
- the type of the environment in which the hearing aid user stayed (speech without background noise, in noise, music, etc.),
- the duration of wearing the hearing aid,
- the preferences as to the use of different hearing programmes.

The information collected during the use of the hearing aid, can be added to the data received by interviewing the patient, and be used by a hearing aid professional at the time of the correction of the hearing aid settings [14]. The data help to correct the hearing programme settings entered by a hearing aid professional and to establish the optimal amplification during the next visits of the user to the hearing care centre. A hearing aid featuring automatic environment classification can activate the programme set for a specific situation [15].

The datalearning function offers automatic optimization of the hearing aid settings and additional training for the user.

6. SUMMARY AND CONCLUSIONS

The human process of hearing sounds, the types of hearing loss or impairment, the diagnostic methods for hearing impairment, and hearing prosthetics together make up a very complex issue. Today, multidisciplinary research teams are involved in testing and preventing hearing loss, as well as in the fitting of hearing aids. The development of these fields of medicine and technology results in the improvement in the quality of life of people in an ageing society.

The World Health Organisation has set 3rd March as the International Ear Care Day in order to draw the public's attention to issues relating to ear conditions, hearing loss, and hearing impairment. Hearing loss is often a chronic disability even in young people. Causes of hearing loss include the noise surrounding us in the modern world.

Modern, technologically advanced, hearing aids are now widely available to the general population.

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POSTĘPY W PROTETYCE SŁUCHU

W pracy dokonano analizy zagadnień związanych z metodami badania i protetyki słuchu pacjentów z niedosłuchem i ubytkiem słuchu. Słuch jest jednym z receptorów, który odgrywa u człowieka ważną rolę w poznawaniu otaczającego świata i orientacji w przestrzeni. Prawidłowe funkcjonowanie narządu słuchu stanowi podstawę komunikacji między ludźmi i rozwoju społeczeństwa. Uszkodzenie lub utrata słuchu zaburza relacje społeczne między ludźmi, powoduje zaburzenia rozwoju u dzieci oraz trudności w nauce. Metody diagnozowania pacjentów i protetyka słuchu stanowią bardzo złożone zagadnienia, którymi zajmują się interdyscyplinarne zespoły badawcze. Rozwój tych dziedzin medycyny i techniki przyczynia się do poprawy jakości życia osób z niedosłuchem lub głuchotą. Przedstawiono w pracy sposoby i możliwości poprawy lub kompensacji ubytków słuchu za pomocą aparatów słuchowych. Wady i ubytki słuchu dotyczą obecnie nawet młodych ludzi. Jedną z przyczyn pogorszenia się słuchu u człowieka jest otaczający nas we współczesnym świecie hałas. Zaprezentowano też w pracy budowę aparatu słuchowego, ze szczególnym uwzględnieniem nowoczesnych rozwiązań technologicznych. Podkreślono, że aparaty słuchowe są obecnie dostępne dla ogółu społeczeństwa.

Słowa kluczowe: percepcja dźwięku, metody badania słuchu, aparaty słuchowe

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Barbara CIECIŃSKA[1]
Tomasz WIĘCEK[2]
Ireneusz GĄGAŁA[3]

LASERS IN INDUSTRY 4.0

In this paper is presented the general idea of the industrial revolution which is called Industry 4.0. The main assumptions and an analysis of the laser use and requirements of lasers for flexible and agile production are presented. Examples of the different technological possibilities when lasers are joined with other machines and IT systems are described.

Keywords: lasers, Industry 4.0 conception, agile production

INTRODUCTION

In the past when the steam engine was invented and became implemented in typical everyday use, the world came into the first age of industrialization. In the factories and workshops the work stands were mechanized and use of the steam engine was in common practice. This was the first industrial revolution. Then together with electricity a new conception of joining together single work stands appeared, the work stands were connected into a production line and the production of products on an even greater scale became possible. This has been named Industry 2.0. The birth of computers and their popularization then gave the possibility of the development of companies on an unknown and previously unprecedented scale. Digitalization processes and the production of more and more efficient integrated circuits, and structures for data processing and control, gave the possibility of continuation of the factories development.

Digitalization, more effective data processing and control systems, and modern software made the production machines more efficient, precise, and added the possibility of connecting them for the creation of flexible production systems. Their integrative parts were both planning and control systems. Digitalization also

[1] Corresponding author: Barbara Ciecińska, PhD, Eng., Rzeszow University of Technology, Faculty of Mechanical Engineering and Aeronautics, Powstancow Warszawy 8, 35-959 Rzeszow, e-mail: bcktmiop@prz.edu.pl
[2] Tomasz WIĘCEK, DsC, Eng., Assoc. Prof., Rzeszow University of Technology, Faculty of Mathematics and Applied Physics, Powstancow Warszawy 6, 35-959 Rzeszow, e-mail: ftkwiece@prz.edu.pl
[3] Ireneusz GĄGAŁA. MsC., TRUMPF Poland, ul. Połczyńska 111, 01-303 Warszawa, e-mail: Ireneusz.gagala@pl.trumpf.com

allowed for a higher level of automatization, which was determinant in the technological development level [1, 2]. This was the time of the third industrial revolution.

Nowadays production activity enters into the stage of Industry 4.0. The assumption behind Industry 4.0 is the integration of different systems and the creation of a network connecting people with machines. The flow of information is designed to go through the various components of the company and the IT department (vertically), and between the machines and the production system (horizontally) [3].

1. THE PLACE OF LASER TECHNOLOGY IN INDUSTRY 4.0

In this section we introduce the concept of industry in the age of computers and robots, where the areas of the plant activity are supported by intelligent systems capable of decision making and automatization. In this concept there are several areas concerning the functioning of plants, such as [3]:

- software – as a tool of integration of different functions,
- collecting and processing of data in the Cloud – which gives possibility of the analysis and decision making based on a huge amount of data stored in one place, available for many people in the same time,
- problems concerning cyber-security,
- artificial intelligence,

and many others relating to the comprehensive computerization of processes and data flow on an unprecedented scale.

The fundamental changes affecting the production and technological aspects of industry are related to an approach to customer and realization of its orders. Till recent times mass production was fundamental. Now the approach is completely changed – the industry has the need to be flexible for individual customer orders. This flexibility is possible thanks to computerized techniques. In the context of flexibility for individual customers the production is called “agile” [4]. In the Fig. 1 is shown the example of the order of one product for one customer. The typical production documents are not required. Tools and machines are selected by the software and saved in memory of the computer, time of production is also calculated.

The laser technology has the potential of making improvements in Industry 4.0. Many producers of lasers implemented new forms of collaboration between customers and system providers. Laser is only the element for performing the machining. The machines equipped in the laser head have possibility of combined technological operations preparation. Then the connection of the modern laser machining and typical, conventional technology (cutting, drilling, thread forming, welding, etc.) with time of carrying out reduction is possible [5].

Technological operations are planned and conducted with the usage of the additional equipment for parts sorting, feeding devices with robots and rational organization of the field of temporary parts storage. In the machines advanced optic systems, state sensors and control systems are required [6]. They give the possibility of data transfer about the state of the machine to the Cloud. Then the communication between machines is possible (Fig. 2.) [7, 8].

Fig. 1. Computerized possibility of individual product ordering

This solution is used in the flexible lines for laser cutting, marking or welding. Sometimes during the logical route of the technological operations a conventional machine appears, like a bending machine for example. Then the produced part does not leave the technological line. Another solution in the laser application is the creation of multi-head systems, which can be used in the selective laser manufacturing in the 3D production area [9].

An additional problem is individual customer order definition from the reason, that properties of the part should be transformed to the machine software language without the errors (the loss of the colors, thickness as the characteristics of the material is possible). At present it is verified and corrected on-line thanks to advanced computerized systems (Fig. 3).

Many producers of laser systems equipped their own production cells with the software for connecting machines. Mass individualization of the production is visible in the SMART industries, where the laser technique is widely used. It has a competitive advantage because of the shorter time of parts manufacturing than in conventional machining, the easiness of cleaning and safety.

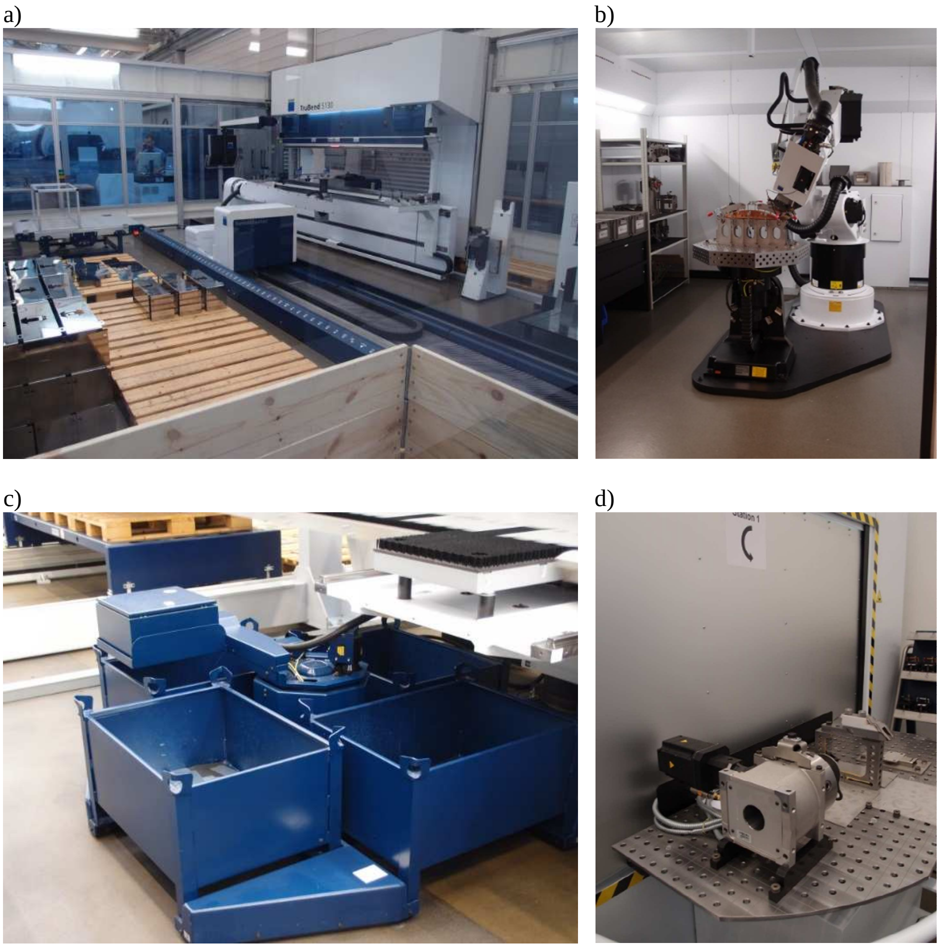

Fig. 2. Combined machines: a) advanced production cell for laser cutting, b) the work stand for laser welding with robots, c) the organization of the work stand for sorting and storage, d) the table with the other part outside of the laser treatment zone, concurrent machining inside the cabin is possible

Lasers are also used for the marking of parts because of the necessity of the fast parts navigation in the treatment space. The part should have individual properties, so it should be possible to tell one from another. Lasers enable the fast encoding of parts for traceability, order number, and quality control [10]. Laser marking is joined also with easy-to-install components like PC, electronics, beam sources, and optics.

Fig. 3. Control on-line of the production state

2. CONCLUSIONS

The diversity of the possible applications of lasers gives a wide range of ways of preparing for integrated, flexible production lines, which can be competitive due to agility in adapting to customer order.

Lasers give the possibility not only for the replacement of typical, conventional work stands, eg. for cutting and engraving, but they can also be a complex manufacturing solution for the identification of the product, its measurement and marking.

Additionally if one producer has the possibility to supply different technological solutions with tailored software, portable and compact, then it can be deliver to the whole plant, where the manufactured assortment follows from customers' orders.

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LASERY W KONCEPCJI PRZEMYSŁU 4.0

W pracy przedstawiono ogólną koncepcję rewolucji przemysłowej nazywanej „Przemysł 4.0". Opisano jej podstawowe założenia oraz przeanalizowano zastosowania laserów w kontekście wymagań elastycznej i zwinnej produkcji. Przedstawiono przykład różnorodnych możliwości technologicznych, jakie dają lasery wspomagane innymi obrabiarkami oraz systemami informatycznymi.

Słowa kluczowe: lasery, koncepcja Przemysł 4.0, zwinna produkcja

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Marek ONAK[1]
Jarosław PSZCZOŁA[2]

AN ARC MELTING SYSTEM WITH A NON-CONTACT IGNITION

Arc melting is a widely used method in materials physics, in general in materials science, as well as in metallurgy, to synthesize new materials starting from high purity constituents. As the high temperature of the technological process is easily attainable, typically arc melting is used to synthesize new materials from metals, and even oxides, with high melting points. In the melting methods usually used the arc is ignited by briefly touching the electrode to the crucible and quickly withdrawing it to a short distance. The contact ignition, however, can contaminate the tip of the tungsten electrode and consequently can reduce the purity of the obtained ingot as compared to the initial components. In order to avoid the contact procedure and thus the purity reduction, an arc non-contact ignition system for melting is proposed in this paper. The arc melting system, the furnace design, the ready for use arc furnace, and the melting procedure, are presented and discussed. Additionally, an arc furnace with a suction attachment to prepare ingots as rods is presented. The clean crystal structures, known from literature, were determined for a number of the compounds synthesized by the non-contact arc method. This quality of crystal structures results mainly from the maintained materials purity during synthesis.

Keywords: arc, melting system, non-contact ignition, furnace design, synthesis procedure, suction attachment, materials purity

INTRODUCTION

The preparation of high-purity metallic alloys or compounds in materials science, materials physics, electronics, metallurgy, is constantly determining challenges for the synthesis procedure [1,2]. The idea is not to reduce the purity of the synthesized material when compared to the purity of the starting constituents. In this respect, materials synthesis by using the arc melting technique is step by step improved. [3-6].

Typically, the widely used arc furnaces consist of a chamber housing an electrically insulated tungsten electrode and a copper hearth (crucible) upon which

[1] Marek Onak, Tarnów Center for Practical and Continuing Education, ul. Szujskiego 13, 33-100 Tarnów, Poland

[2] Autor do korespondencji/corresponding author: Jarosław Pszczoła, Faculty of Mathematics and Applied Physics, Rzeszów University of Technology, al. Powstańców Warszawy 12, 35-959 Rzeszów, e-mail: j.pszczola@prz.edu.pl

the sample is melted [1,2]. The DC (direct current) arc is initiated by electrical contact between the tungsten electrode tip and the copper hearth. The hearth is internally water cooled and thus the container/melt reaction and consequently the melt contamination is excluded even with the highest melting point metals. Nevertheless, the so-called non-consumable tungsten electrode contaminates the melt with materials of this electrode and the crucible as a result of the contact ignition.

Fortunately, the development of the TIG (abbreviation: tungsten inert gas) welding method enables one to also overcome this difficulty. In this case, the inverter welder with the HF (high frequency) non-contact arc ignition as a power supply for the arc system can be applied [4]. An arc melting system using this power solution in order to omit the contact ignition of the arc during the melting procedure is proposed in the present paper.

1. THE ARC MELTING SYSTEM

The arc melting system with non-contact ignition applied to materials synthesis has been developed (Figs 1, 2). The arc melting furnace (1) is surrounded by the supplementary elements: the lamp or a non-contact temperature meter (2), the inert gas system (3), the power supply unit (4), and the vacuum pump (5).

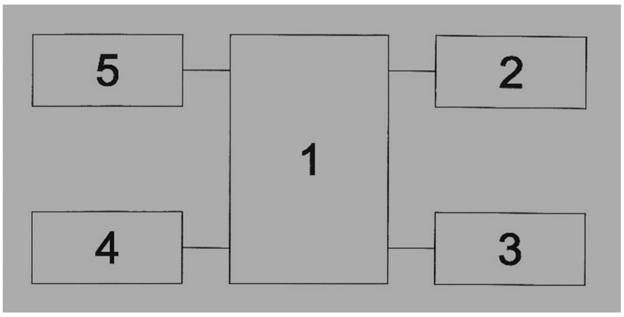

Fig. 1. Scheme of the arc melting system with non-contact ignition composed of: arc furnace (1), lamp (2), inert gas system (3), power supply (4) and vacuum pump (5)

The lamp (2) is sometimes used to light up inside the melting chamber in order to inspect through the other window the starting constituents before melting. The inert gas system (3) is composed of a steel bottle, the container of high purity argon gas, under a pressure 200-300 bar. Before using the shielding gas the high pressure must be reduced to a suitable working pressure. The next necessary component of the system is therefore a pressure-reducing valve with a gauge where the current pressure of the outflow gas can be read. The inert gas is introduced to the melting chamber of the arc furnace through the blocking valve attended by the pressure meter, which is attached to the melting chamber. The power unit supply (4) is the typical inverter TIG welder [4] equipped with a high frequency facility for ignition of the arc. In the power unit supply inverter technology is used [7-10]. Namely, in the inverter the power supply from a standard 50 Hz electrical current from the electric grid is used. However, instead of being fed directly into a transformer (as in the old welder version), it is first rectified to 50 Hz DC.

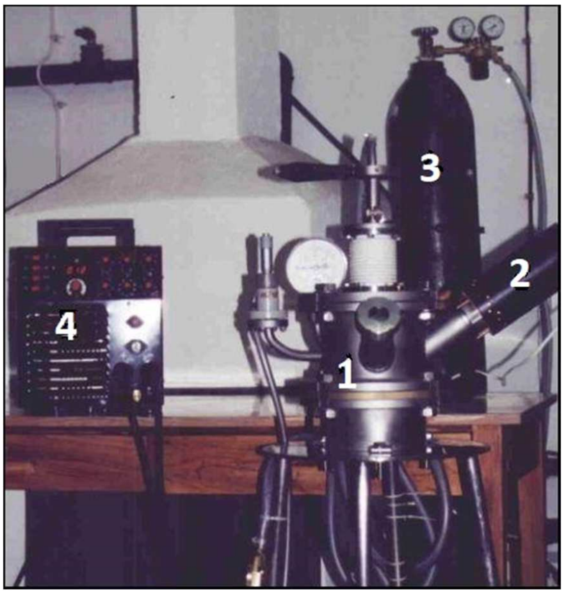

Fig. 2. Arc melting system with non-contact ignition: arc furnace (1), lamp (2), inert gas system (3), power supply (4) and vacuum pump (5) – not presented

The current is then fed into the inverter section of the power supply where it is switched on and off by solid state switches at frequencies as high as 20 000 Hz. Subsequently, this pulsed, high voltage, high frequency, DC is fed to the main power transformer, where it is transformed into a low voltage 20 000 Hz DC suitable for welding or melting. Finally it is put through a filtering and rectifying circuit. Output control is performed by solid state controls which modulate the switching rate of the switching transistors. The main power transformer, which operates at 20 000 Hz is vastly more efficient than 50 Hz transformers, which means that it is much smaller and thus the weight and dimensions of the welder are distinctly reduced. As a rule, the TIG welder supplies are equipped with an ignition facility. This facility is a high frequency unit (HF) which increases the frequency to 2-4 million periods per second and the voltage to several thousand volts. These parameters are suitable to strike a spark between the tungsten electrode and the crucible with the charge, to create a conductive path through the shielding gas, and thus to strike the melting arc. The vacuum pump (5) is composed of the rotary and the diffusion units as well as the vacuum meters. The outlet of the vacuum pump is connected to the exhaust ventilation system in order to remove the pollution which can appear from the melting chamber during the melting process.

2. THE MELTING CHAMBER

The new construction of melting chamber with the non-contact arc ignition, and thus with non contact melting was designed (Fig. 3). At the bottom of the figure the cooler (1) made of stainless steel is presented. Inside of the cooler the water flow distributor (2) is located. The water inlet (26) and the water outlet (27) are welded to the cooler. The cooling water is directed by the flow distributor (2) onto the lower surface of the crucible housing (3) which is made of brass. On the front of the crucible housing the replaceable cold crucible (4) with a hollow for a charge is mounted. It is possible to use crucibles with hollows of different shapes. In the hollow of the cold crucible the starting materials to be synthesized (charge) are placed before melting. The cold crucible (4) also composes the positive electrode of the furnace electrical system. The contact of the cooler (1) and the crucible housing (3) are sealed by the rubber o-ring (5).

The melting chamber (6) is mounted on the crucible housing (3). These two parts (6 and 3) are easily held together by the thick screw joints (23) attached to the side cuttings in the flanges (the fast fittings, see Fig. 2). The melting chamber (6) is equipped with the window system that is the sight glass (8) which can be used for inspection of the melting process, or to fix a lamp or to fix the non-contact temperature control system. Similar sight-glass is located in the front of the melting chamber (6). Terminals for the vacuum pump (10), for the pressure meter (20, terminal not visible), for the inert gas inlet (21, 22) and for the safety valve (25) are present on the melting chamber sides. The melting chamber (6) is covered with the chamber lid (11).

The essential part for the non-contact arc ignition is composed of several elements (Fig. 4). Namely, in the central part at the bottom surface of the lid (11) the sliding rings (13) made of teflon are attached by the holding ring (24). These sliding rings fix the placement of the ball guide (14), also made of teflon. Use of the electrically isolating teflon for these elements enables the non-contact melting in the arc furnace. These teflon elements (13,14) with well-chosen dimensions, as well as the teflon bellows (15), exclude a parasitical arc between the electrode tube (12) and the chamber lid (11). Here it can be added that as a rule in the contact ignition arc systems stainless steel bellows and phosphor bronze balls are used [1, 2]. The non-contact ignition melting procedure excludes this solution.

The ball guide (14) is pressed indirectly to the chamber lid (11) by the holding ring (24). The electrode tube (12) that is the handle of the tungsten end electrode (7) can move throughout the ball guide (14). The electrode tube (12) and the tungsten end electrode (7) form the negative electrode of the furnace electrical system. The electrode tube (12) is equipped with a welded flange which covers the top of the teflon bellows (15) in a vacuum tight manner. The divided ring (19) clamps the bellows (15) to the flange. Similar rings fix the bellows (15) to the chamber lid (11).

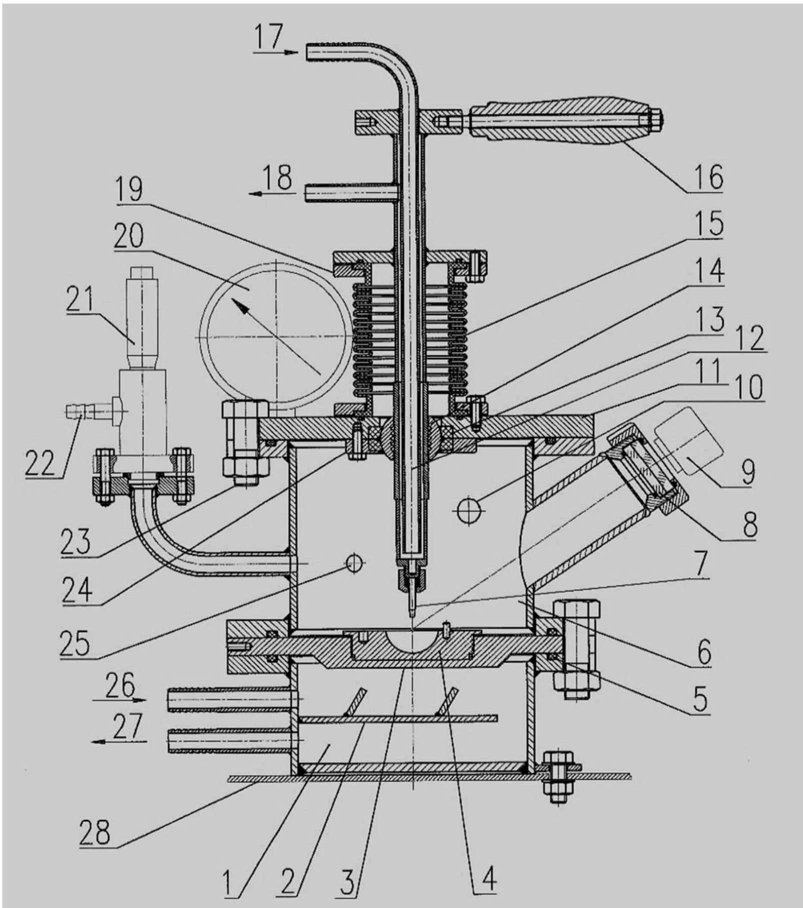

Fig. 3. Design of the main part of the electrical arc furnace devised for the non-contact arc ignition. Components numbered 1–28 are as follows: 1 - cooler, 2 - flow distributor, 3 - crucible housing, 4 - cold crucible, 5 - O-ring, 6 - melting chamber, 7 - tungsten end electrode, 8 - window, 9 - lamp, 10-connection to vacuum pump, 11 - chamber lid, 12 - electrode tube, 13 - sliding rings, 14 - ball, 15 - bellows, 16 - handle, 17 - water inlet, 18 - water outlet, 19 - divided ring, 20 - pressure meter, 21 - metering valve, 22 - inert gas inlet, 23 - screw joint, 24 - holding ring, 25 – connection to safety valve, 26 - water inlet, 27 - water outlet, 28 - supporting table

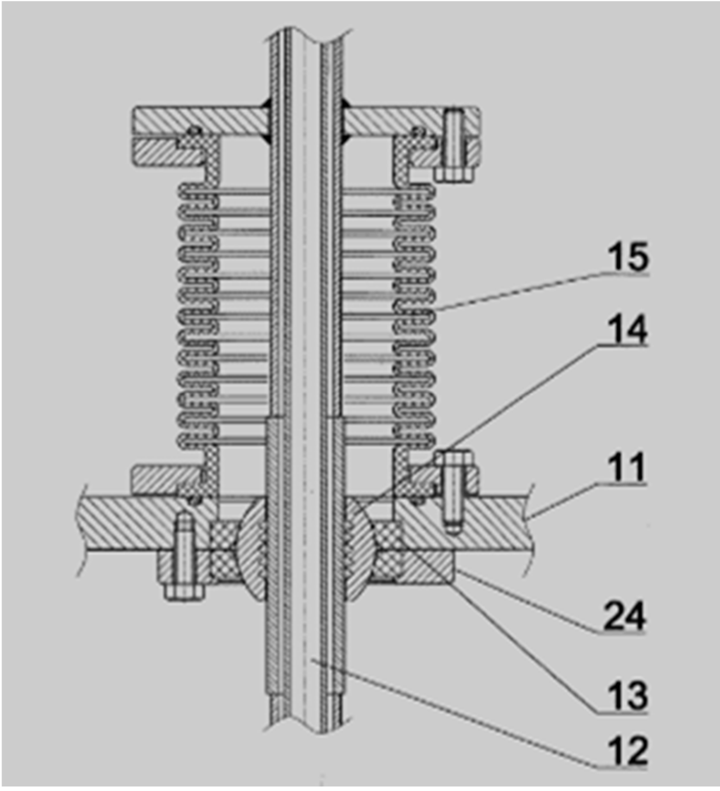

Fig. 4. A cross section of the part essential for the non-contact ignition composed of the bellows made of teflon (15), the electrode tube made of stainless steel/copper (12), the guide ball made of teflon (14), the sliding rings made of teflon (13), the holding ring made of stainless steel (24), the lid made of stainless steel (11), and the divided ring (19)

The teflon bellows (15), the ball guide (14), and the sliding rings (13) electrically isolate the negative electrode tube (12) as well as the tungsten end electrode (7) from the chamber lid and thus from the rest of the furnace, including the positive electrode (4).

The upper part of the electrode tube is equipped with electrically isolating handles (16) with acorn nuts, all made of teflon.

The handles (16), the bellows (15), and the ball guide (14) enable both the displacement of the electrode (7) and its deviation from the vertical.

The water inlet (17) and the water outlet (18) connected to the electrode tube (12), which is concentrically double tubed, form the water cooling system of the negative tungsten end electrode (7). The complete furnace is mounted on a supporting table (28).

3. THE BASIC SYNTHESIS PROCEDURE

The high temperature synthesis procedure using the arc melting system with non-contact ignition is a simple and convenient method. After introducing the components to be melted into the hollow of the cold crucible (4), the melting chamber (6) is covered with the chamber lid (11). The distance between the tungsten end electrode (7) and the charge in the crucible (4) is then approximately equal to 10–15mm.

As a next step, the distance muff with a semicircle C-letter type cross section made of polyamide is interposed between the chamber lid (11) and the flange of the electrode tube (12) (Figs 2, 3). The distance muff precludes an excessive compression of the bellows (15), and thus precludes a shift of the end tungsten electrode (7) into the charge during the pumping procedure. Subsequently, air is evacuated from the melting chamber (6) and also from the bellows (15) using the vacuum pump system. After attaining the required vacuum level the connection to the pump (10) is closed and the melting chamber (6) is filled up with the high purity argon gas from the inert gas system. In order to remove the rest of the oxygen the pumping and the argon lavage is repeated several times. Usually, the melting chamber (6) is filled up with argon up to atmospheric pressure or slightly higher, which is controlled by the pressure meter (20).

Argon, an inert gas, cannot react with the other elements during the melting process. Moreover, this shielding gas plays an important role in connection with the transfer of current and heat in the arc. After almost filling up with argon, the distance muff is removed and the mobility of the electrode tube system (7,12,15,16) is recovered. Afterwards, the cooling water system is included (17,18), the high frequency tungsten inert gas (TIG) power supply is switched on and the arc, ignited in the non-contact manner inside the melting chamber (6), begins to work. It should be emphasized that this pilot arc does not do any melting, but it is needed to start the proper melting arc without touching the tungsten electrode to the crucible. Inert gas atoms are ionized by losing electrons and leaving a positive electric charge. Then the gas ions flow to the negative pole (tungsten electrode) and the negative electrons flow to the positive pole (crucible with charge). This is the so-called electrode negative polarity melting procedure. Reverse polarity can also be used, however in this case the current carrying capacity of the tungsten electrode is extremely low. Moreover, small fragments of the charge are launched from the crucible by this sort of arc.

The non-contact arc melting procedure is presented in Fig. 5. The working arc inside the chamber illuminates the window (Fig. 5-1). The glowing arc occuring between the tungsten end electrode and the distanced from it cold crucible melts the sample (Fig. 5-2). The tungsten end electrode, the cold crucible, and the synthesized drop, as they are after the arc is switched off, are presented in Fig. 5-3; the considerable distance is visible. The result of the melting procedure, the solidified drop inside the opened melting chamber is shown in Fig. 5-4.

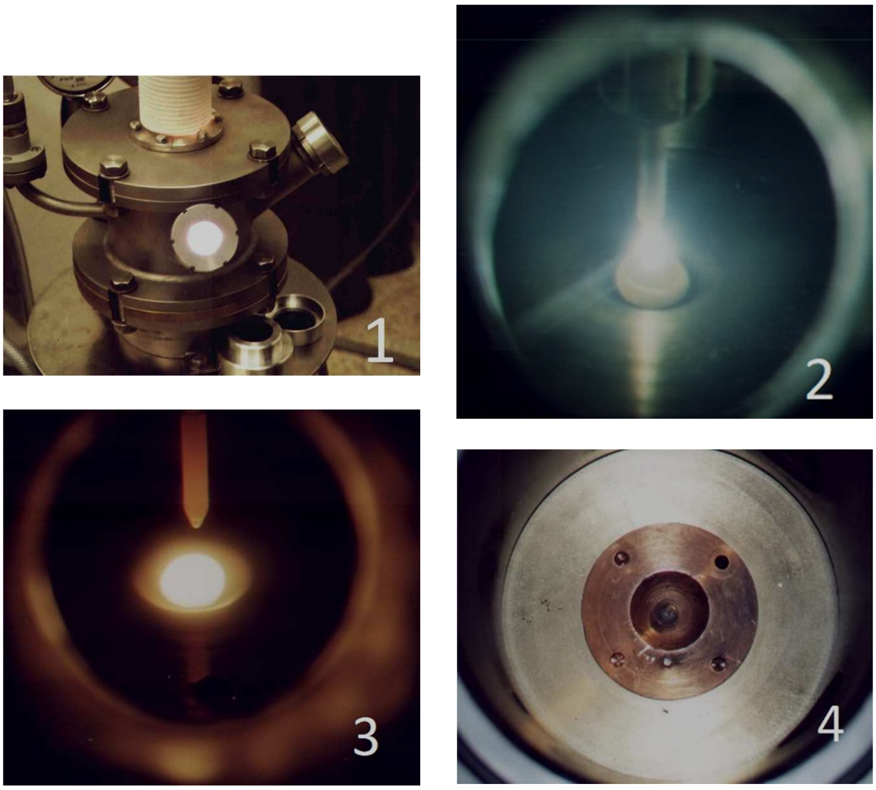

Fig. 5. The non-contact arc melting is switched on (1, 2) – ultraviolet radiation prevails, the synthesized drop after the arc is switched off (3) – red radiation prevails and the solidified drop inside the opened melting chamber (4)

4. THE TUNGSTEN END ELECTRODE

The fundamentally important tungsten end electrode is prepared from rods of pure tungsten metal. Tungsten is a metal with both and extremely high melting point, 3695K, and boiling point, 6203K. Thus the tungsten melting and boiling points are more than double as compared to the melting and boiling points of iron (1811K and 3134K respectively), cobalt (1768K and 3200K) or nickel (1728K and 3003K). Therefore the tungsten electrodes are treated as standards in the TIG welding and arc melting procedures.

Nevertheless, alloying the tungsten with a few per cent of certain metal oxides (ThO_2, ZrO_2, LuO_2, CeO_2) improves the electrode properties. Thorium oxide especially is predicted to improve the electrodes for the TIG welding method. However, the tungsten electrodes with the addition of the thorium oxide are slightly alpha-radioactive and thus inhalation of ground thorium dust, smoke containing thorium, or fumes containing thorium, is hazardous for health. Evidently, these thorium content pollutants radioactively contaminate the environment. Therefore the use of thorium electrodes (in market marked with red colour) during the arc melting procedure in the arc furnaces should be definitely refused.

There is a relationship between the electrode and the melting (welding) arc. Namely, parameters of the arc depend to some extent on the dimensions, end shape and the grinding of the electrode [7-10]. The diameter of the electrode should be adjusted for the current intensity. When welding is done with a direct current and the electrode polarity is negative, the electrode point should be conical in order to obtain a concentrated arc that will provide a narrow and deep penetration profile. A small pointed angle gives a narrow weld pool and the larger pointed angle gives the wider weld pool. Blunting the electrode point to make a flat area can increase the lifetime of the tungsten electrode. Additionally for the welding procedure the grinding traces for the electrode point should lie along the electrode in order to obtain a narrow weld pool.

These restrictions are not necessarily suitable for the arc melting process. Namely, often a wide arc is necessary to perform an efficient melting process. In this case, the flattened electrode point or even the electrode with a half globular form extends the arc wide. Moreover, circular grindings of the electrode point introduce an umbrella-like shape to the arc. The hemispherical cavity inside the cold crucible (4) (Fig.3) stabilizes the umbrella-like shape of the melting arc. This shape of the arc is advantageous for the melting procedure. As a result of not too large a travel down the electrode tube (12) with the tungsten end electrode (7) the umbrella-like arc pushes the charge in the crucible and melts it as a whole almost immediately. A standard type arc also can melt the charge. This arc can be directed throughout the charge by using the handles (16) to melt all the charge constituents together.

5. FURNACE WITH THE SUCTION CHAMBER

Figure 6 presents the version of the arc melting furnace with the system designed to prepare rods from the melt. The upper part of the furnace is identical to the basic version (Fig. 3), but different numbers are used to identify particular components. Nonetheless the construction of the lower part of the furnace is considerably different. In this case, the crucible housing that is the suction chamber (3), equipped with the connection to the vacuum pump (31), is mounted to the cooler (1). This cooler is without the flow distributor. The main plate of the cold crucible (4) is settled on the cooler (1) whereas its central conical part connects by lower tailpiece with the crucible housing (3). Inside of the cold crucible (4) the divided cold crucible (5) is fixed by the clamp ring (7). The charge to be melted is placed inside of the hollow of the divided crucible (5).

The arc furnace, with the cooler (1) situated directly above the circular table (30) and the suction chamber (3) situated directly under the circular table (30), is presented in Fig. 7.

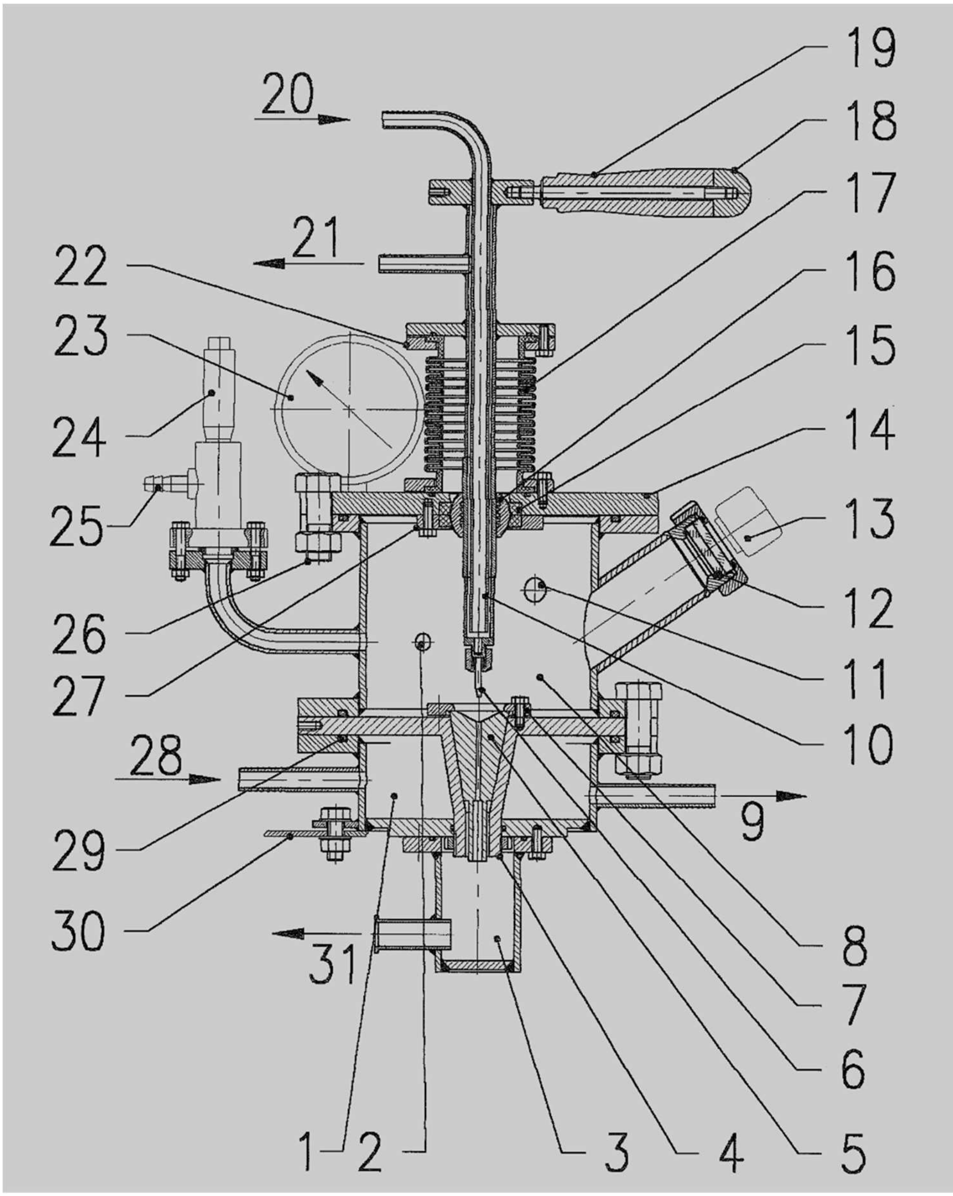

Fig. 6. The design of the arc furnace with an suction attachment composed of cooler (1), crucible housing (3) equipped with the vacuum outlet (31), cold crucible (4), divided cold crucible (5) and clamp ring (7), all fixed to the melting chamber (8)

As mentioned above, inside the suction attachment the divided cold crucible (5) is placed. This divided cold crucible is presented as a whole and in parts in Fig. 8.

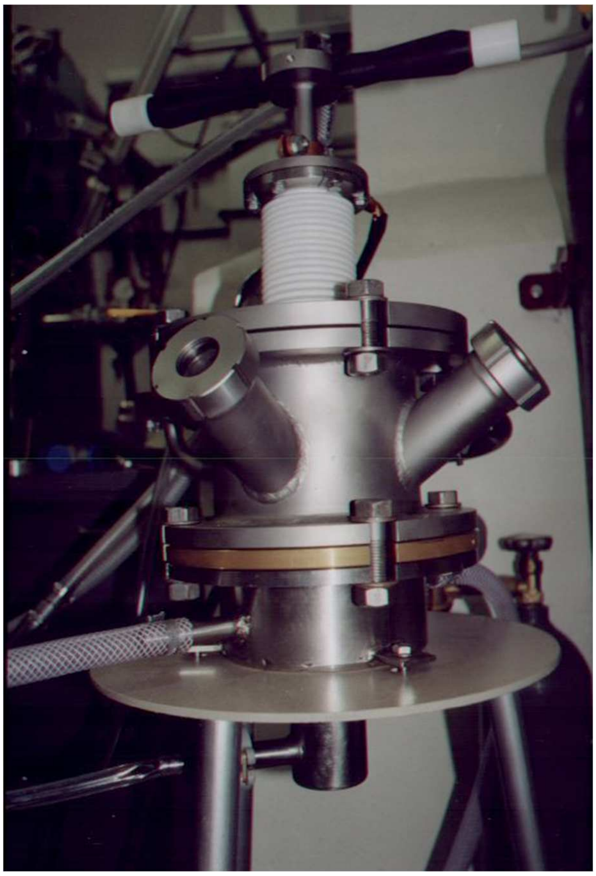

Fig. 7. The arc melting system with the suction attachment which is visible immediately above and under the circular table

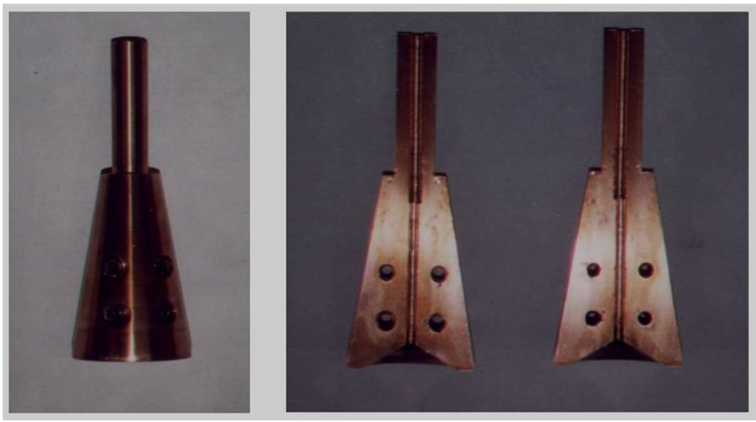

Fig. 8. The divided cold crucible as a whole (left) and in parts (right)

In practice, divided cold crucibles with different diameters of holes are used. However these diameters are in the 0.5–3mm range.

6. A SYNTHESIS WITH THE SUCTION OF THE MELT

The first steps of the synthesis procedure with the suction chamber are similar to those discussed above. Nevertheless, after complete melting of the starting materials, which are placed inside the hollow of the divided crucible (5), the rapid vacuum pumping of the crucible housing (3) (the suction chamber) is included shortly through the vacuum pump outlet (31) (Fig. 6), the drop melt is sucked into the hole of the divided cold crucible (5) and after that the melt is immediately solidified into the rod form (Fig. 9).

Fig. 9. Exemplary cast rods prepared using the furnace with the suction attachment

7. SUMMARY

The above described arc melting system and particularly its main component, the arc furnace with the non-contact ignition, has been used and tested many times. Hundreds of new crystallographically clean compounds, alloys and even ceramics have been synthesized for scientific and practical purposes (for instance [3,6,11-13]). The clean crystal structure mainly follows the purity of the solidified melt of these materials.

The presented furnace and thus the arc melting system has a number of advantages. First of all, the arc system and especially the furnace is convenient and easy to operate. Here, it can be added that the applied power supply unit enables control of the arc current and thus control of the arc power used for melting [4]. The melting chamber can be easily disconnected before a cleaning-up procedure using the side fast fittings (Figs 2, 3, 7). Vacuum- or air-tightness is maintained by the o-rings placed in circular u-grooves on particular parts of the melting chamber.

Two sight-glasses aimed at the middle of the cold crucible can be used for inspection of the melting process, for non-contact appreciation of the temperature of the melt or to light up the melting chamber inside. In order to protect ones vision the melting process must be observed using welding safety goggles with proper filter lenses. These must filter out harmful infra-red and ultra-violet rays emitted from the melting arc, and reduce visible light to a level which is sufficient to see the melting process without straining the eyes. Alternatively, the sight-glasses must be equipped with the cover windows composed of the proper filter lenses [7-10,14]. Windows of the sight-glasses are easily disassembled in order to clean up the lenses.

Both the crucible housing close together with the crucible and the electrode tube with the tungsten end electrode are intensively cooled by the water system. The negative pole of the welder is connected by cable to the electrode tube to establish the electrically negative electrode, whereas the positive pole of the welder is connected by a second cable to the flange of the crucible housing to form the positive electrode from the crucible and the rest of the melting chamber. The isolating handles with the acorn nuts prevent electrical shock during melting and also during high voltage ignition. Nevertheless, during the melting procedure all welding safety rules should be fulfilled. Suitable shoes, protective apron and welding gloves must be used [7-10,14].

It can be emphasized, that the presented arc-melting system, well-tested in practice, can be treated as useful equipment in scientific or technological laboratories as well as factory equipment for a high-tech production on a small scale. The bigger arc melting system with non-contact ignition can of course be developed for a higher scale of production. Moreover, it can be mentioned that the next step for further studies is to test the microscopic metallurgical properties of the obtained ingots.

Acknowledgements

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ZESTAW DO TOPIENIA W ŁUKU ELEKTRYCZNYM Z BEZKONTAKTOWYM ZAPŁONEM

Topienie w łuku elektrycznym jest metodą szeroko używaną w fizyce materiałów, w ogólności w nauce o materiałach, jak również w metalurgii do syntezy nowych materiałów ze składników o wysokiej czystości. Z reguły łuk elektryczny jest używany do syntezy nowych materiałów z wysokotopliwych metali a nawet tlenków, gdyż łatwo jest uzyskiwana wysoka temperatura w tym procesie. W typowych metodach topienia łuk elektryczny jest zapalany przez krótki kontakt a następnie oddalenie elektrody od tygla na niewielką odległość. Taki kontaktowy zapłon może jednakże zanieczyścić końcówkę elektrody wolframowej i w następstwie obniżyć czystość otrzymanego wytopu w porównaniu ze składnikami wyjściowymi. W celu uniknięcia procedury kontaktowej i tym samym redukcji czystości w pracy jest zaproponowany zestaw do topienia z bezkontaktowym zapłonem łuku elektrycznego. Zestaw do topienia w łuku elektrycznym, projekt pieca, gotowy do użycia piec, proces topienia są przedstawione i dyskutowane. Dodatkowo jest przedstawiony piec łukowy z przystawką ssącą do otrzymywania wytopów w kształcie prętów.

Czyste struktury krystaliczne znane z literatury, otrzymano dla wielu związków syntetyzowanych metodą łuku elektrycznego z bezkontaktowym zapłonem. Jakość struktur krystalicznych wynika głównie z utrzymania czystości materiałów podczas syntezy.

Słowa kluczowe: łuk elektryczny, zestaw do topienia, bezkontaktowy zapłon, projekt pieca, proces syntezy, przystawka ssąca, czystość materiałów

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Marta SZMYD[1]
Dariusz PALIGA[2]
Andrzej WASILEWSKI[3]

INFLUENCE OF THE SURFACE CONDITION ON THE ADHESION OF COMPOSITE MATERIALS TO ENAMEL

This work presents a method of measuring the maximum stress that a composite sample fixed on a tooth surface will withstand. The test was carried out for 3 different surface conditions of enamel: no processing, after treatment with a diamond drill, and after treatment with a diode laser. The force of adhesion was measured in an Instron 5960 testing machine. The results demonstrate a significant effect of the surface condition on the adhesion of the composite to the enamel.

Keywords: strength machine, dental treatment, laser, drill

INTRODUCTION

Conservative dentistry is a dynamically developing field of medicine. Everyone dreams about healthy teeth and a nice smile. The role of dentists and the team working on the quality of dental materials is to make the most durable fillings, similar (especially in external appearance) to tooth enamel.

1. AIM

The purpose of the work was to determine the value of the maximum shear stress at which the composite material breaks away from the enamel. It is assumed that the condition of the tooth surface will affect the value of stress. The studies considered three surface conditions most frequently used by dentists:

a) enamel without treatment,
b) enamel after machining with a drill, and
c) enamel after laser treatment.

[1] Corresponding author: Marta Szmyd, student, Rzeszow University of Technology, Powstancow Warszawy 8, 35-959 Rzeszow, Poland, e-mail: szm1@o2.pl
[2] Dariusz Paliga, Rzeszów, Dental Practice
[3] Andrzej Wasilewski, Rzeszow University of Technology, Powstancow Warszawy 8, 35-959 Rzeszow, Poland

2. IMPORTANT CONCEPTS

Adhesion is the tendency of dissimilar particles or surfaces to cling to one another (cohesion refers to the tendency of similar or identical particles/surfaces to cling to one another)[1]. IUPAC definition of adhesion , it is the process of attachment of a substance to the surface of another substance

Maximum tangential stress – the adhesion force is the maximum tangential stress (force exerted on the surface) at which the composite loaded with shear force F will break away from the enamel surface.

We calculate the maximum tangential stress from the formula [2]:

$$\tau_{max} = \frac{F_{max}}{S} \quad \left[\frac{N}{m^2}\right] \tag{1}$$

F_{max} – maximum load at which the composite will break,
S – contact surface of the composite with the tooth.

3. THE EXPERIMENTAL METHOD

A tooth immersed in acrylic with a composite attached to the surface was placed in a testing machine. A load was applied to the composite sample.

Figure 1 shows a schematic of the experimental set up.

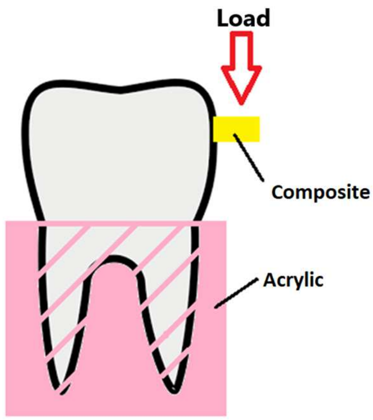

Fig. 1. Adhesion measurement scheme

4. ENAMEL TREATMENT

Drill processing

The first way used to process the enamel was to treat the surface with a drill. A diamond drill bit with a grain size of approx. 150 μm was used. Diamond drills are made of high quality stainless steel which is covered with industrial diamond filings. Thanks to the advanced production technology of diamond drills, it is possible to obtain the desired granularity [3].

Laser treatment

During the experiment, the Lasotronix Smart M laser diode was used with a 0.2 mm optical tip.

Laser parameters:

a) wavelength – 980 nm

b) power – 2W

c) operating mode – pulse mode, the duration of the pulse being equal to the duration of the interval between pulses and 100 μs

d) frequency – 5 kHz.

The beam of light was introduced in such a way that the optical fiber touched the surface of the tooth. Without removing the end of the optical fiber, the beam was moved linearly along the surface (surface contact technique). Thanks to this technique, power losses were avoided [4].

5. IMAGE OF ENAMEL AFTER TREATMENT

In order to compare the surface of the teeth after processing, they were viewed under a microscope. A scanning electron microscope (SEM) was used for observation.

The pictures show:

a) enamel without treatment (Fig. 2),
b) enamel surface after drill treatment (Fig. 3)
c) enamel surface after laser treatment (Fig. 4).

Surface roughness of the enamel

On the basis of the above images, we can conclude that enamel after treatment with a drill has a greater roughness. Therefore, the composite should better adhere to the enamel after being treated with the drill bit.

6. MATERIALS AND EQUIPMENT USED IN THE EXPERIMENT

Preparing for the experiment, special metal moulds were designed, which were later used to make a silicone cast – an acrylic mould and a composite mould. The necessary materials were purchased, such as a composite, an intermediate layer, phosphoric acid for etching the surface and materials for sample preparation.

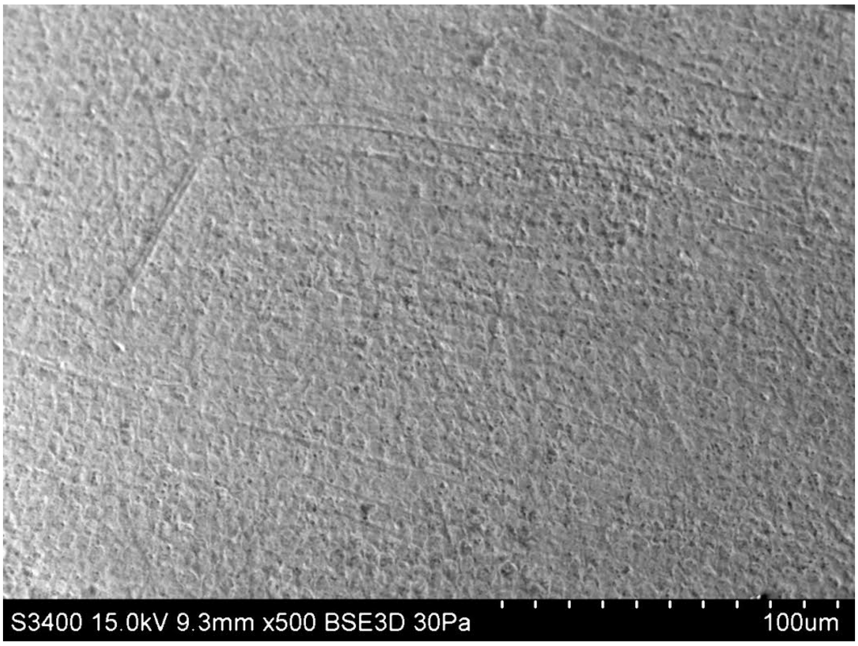

Fig. 2. Image of enamel without processing, magnification 500x

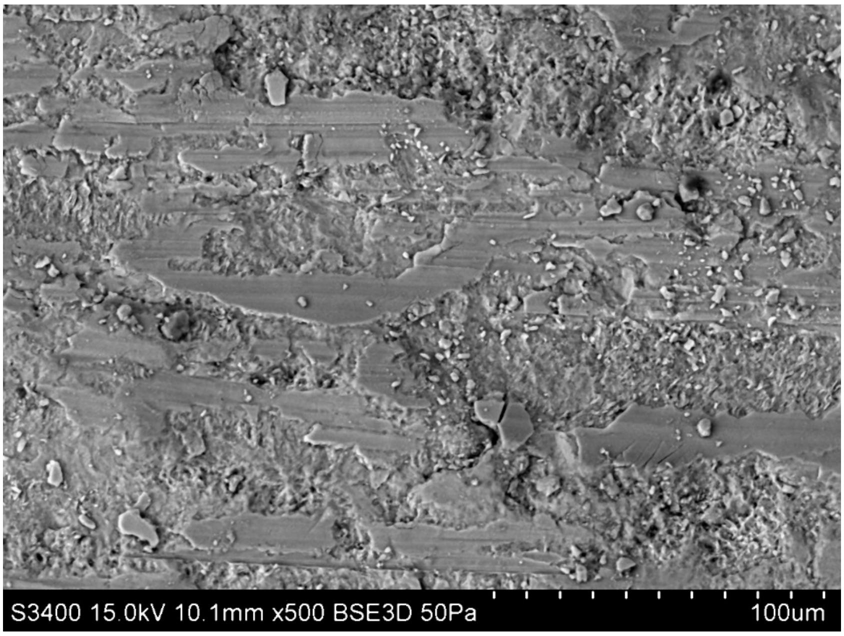

Fig. 3. Image of enamel after drill treatment, magnification 500x

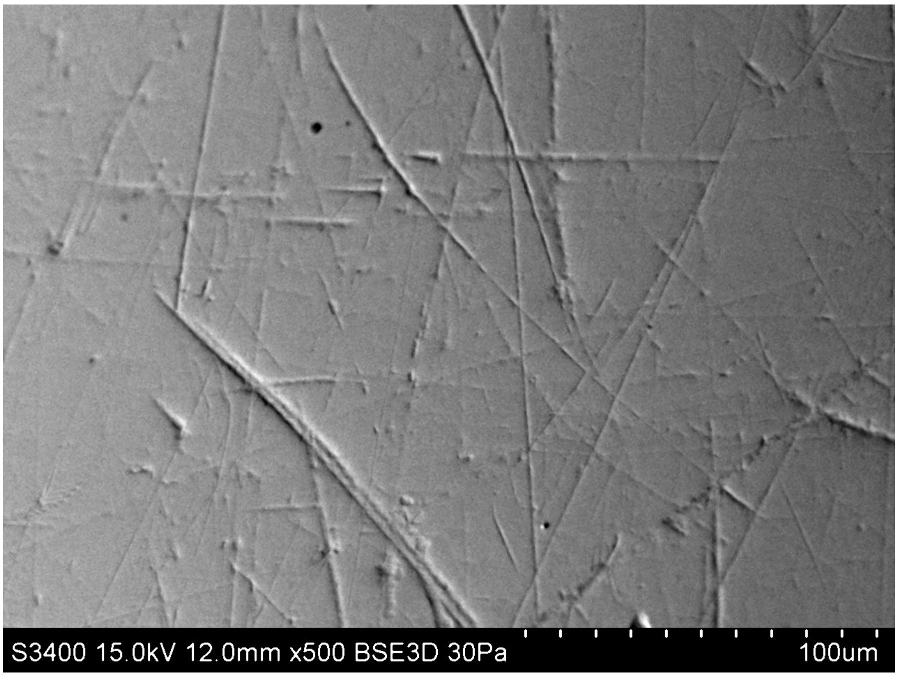

Fig. 4. Image of enamel after laser treatment, magnification 500x

Composite

Boston's Arkona is a light-curing composite.

Applications of composites is like as [5]: for prosthetic restorations, fillings for all classes of cavities, for bridges and crowns, for the concept of stability rails.

The Boston composite consists of [5]:

- an organic base matrix (bisphenol A diglycidether dimethacrylate, diurethane dimethacrylate, triethylene glycol dimethacrylate)
- inorganic solid fillers (barium-aluminum-silicate glass, fire silica, titanium dioxide)
- additional substances (photoinitiators, inhibitors, digestive, stabilisers, pigment)

Intermediate layer

Gluma 2 Bond manufactured by Heraus is a light-curing interlayer between enamel and composite.

In dental practice it is used to [6]:fix composite fillings, fix ceramic fillings, and for the treatment of tooth hypersensitivity.

The bond consists of [6]:

- Methacrylate
- Ethanol

- Photoinitiator
- Glutaraldehyde
- Fillers

Endurance machine

In the experiment, the INSTRON model 5960 machine, the Instron Bluehill software package and several own components were used.

7. THE COURSE OF THE EXPERIMENT

he experiment was carried out in several stages. Initially, the density of the composite was determined, then a vice handle, mechanical elements and silicone moulds were designed and made.

Stages of fixing the composite on enamel:

1. Fixing the teeth in the actyl

Acrylic was prepared by a mixture of self curing powder and a monomer (liquid) according to the following instructions by volume: 3 parts powder and 1 part liquid.

The monomer was poured into the powder and mixed for approximately 30 seconds to obtain a homogeneous consistency. The solution was then poured into a silicone mould. After about 3 minutes, when the consistency was dense enough, a tooth root was placed in it.

2. Preparation of phosphoric acid solution

Before proceeding with direct sample preparation, 100 ml of 37.5% orthophosphoric acid solution was prepared, by mixing 44 ml of 85% orthophosphoric acid solution with 56 ml of water.

3. Direct sample preparation

Each sample was prepared by the following steps:

a) The acid was applied to the enamel surface.
b) Waited 20s.
c) The tooth was splashed with water spray for 20s.
d) The sample was partially dried to reach optimum humidity for the purpose of experiment.
e) Bond layer – intermediate layer was applied, and rubbed for 30s.
f) The sample was blown again.
g) The sample was exposed to a polymerization lamp.
h) The composite was applied to the prepared place.
i) The sample was exposed again.

Samples (Fig. 5) were then suitably placed in a testing machine.

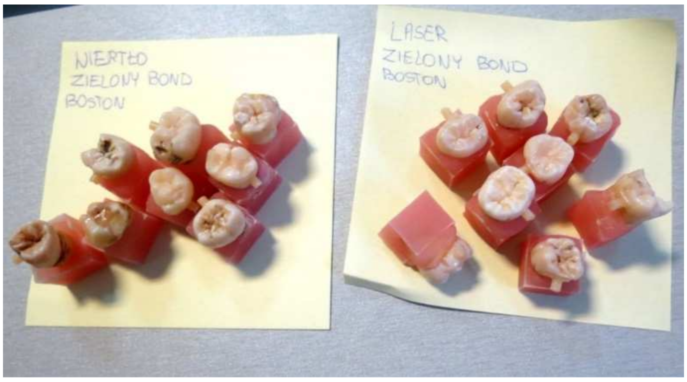

Fig. 5. Samples ready for measurement

4. Measurement of the adhesion force in a strength machine
   a) Attaching the sample to the vice handle

A sample was placed in the previously prepared vice handle. The bolt was then tightened with the omni-key to prevent the sample from moving.

   b) Placement of a vice handle with a sample into the machine

The next step was the precise placement of the vice handle with the sample in a strength machine. Stable mounting was possible thanks to the pneumatic clamps of the machine.

   c) Positioning of the sample

An important aspect was the exact location of the plaque relative to the tooth surface. This allowed the exact measurement of the load at which the sample was broken.

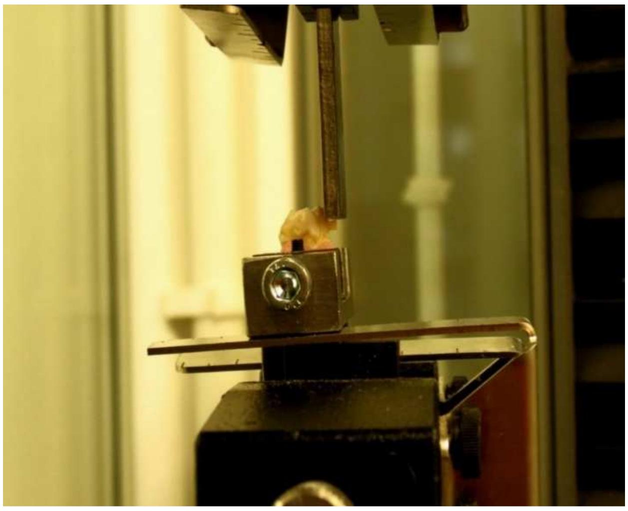

Fig. 6. Sample in the strength machine

8. OBSERVATION OF THE DETACHMENT OF THE COMPOSITE

The plate was moving at a speed of 0.5 mm/min. By connecting the testing machine with the computer it was possible to follow the course of the experiment on an ongoing basis. The values of forces in the displacement function were observed on the monitor. It was possible to compare the test results with previous samples.

9. RESULTS OF ADHESION FORCE MEASUREMENTS

The developed method of measuring the adhesion force turned out to be effective. The presented results have a large discrepancy due to the diverse state of the enamel surface.

Received results

For each case, the maximum shear stress was calculated according to formula (1).

Table 1. Values for glaze samples without treatment

Lp.	Sample label	Maximum load F [N]	Maximum tangential stress τ_{max} [MPa]
1	sample_1	14,61	4,65
2	sample_2	17,68	5,63
3	sample_3	22,14	7,05
4	sample_4	70,66	22,49
5	sample_5	55,39	17,63
6	sample_6	20,88	6,65
7	sample_7	69,43	22,10
8	sample_8	64,61	20,57
Average		41,92	13,35
Standard deviation		25,20	8,02

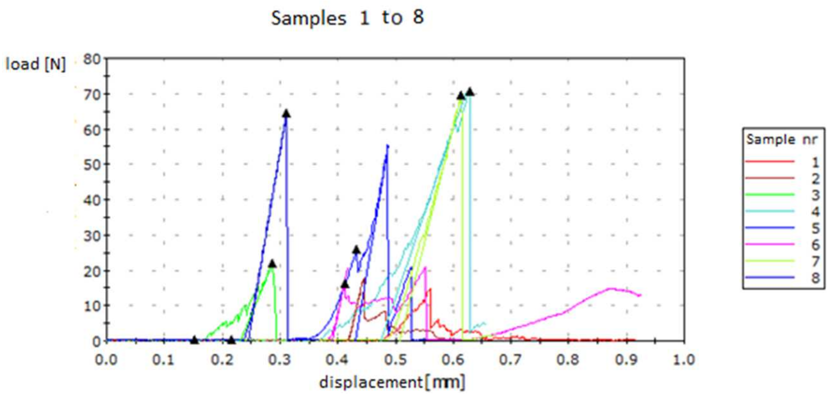

Fig. 7. The dependence of the load on the movement of all glazed specimens without processing

Average tangential stress maximum with uncertainty for the enamel without treatment:

$$\tau_{max_{śr}} = 13{,}4 \pm 8{,}5 \quad [MPa]$$

Table 2. Values for glaze specimens after machining with a drill

Lp.	Sample label	Maximum load F [N]	Maximum tangential stress τ_{max} [MPa]
1	sample_1	40,20	12,80
2	sample_2	31,50	10,03
3	sample_3	44,50	14,16
4	sample_4	77,83	24,77
5	sample_5	43,32	13,79
6	sample_6	68,49	21,80
7	sample_7	46,20	14,71
Average		50,29	16,01
Standard deviation		16,55	5,27

Average tangential stress maximum with uncertainty for the enamel after brazing:

$$\tau_{max_{śr}} = 16{,}0 \pm 5{,}6 \quad [MPa]$$

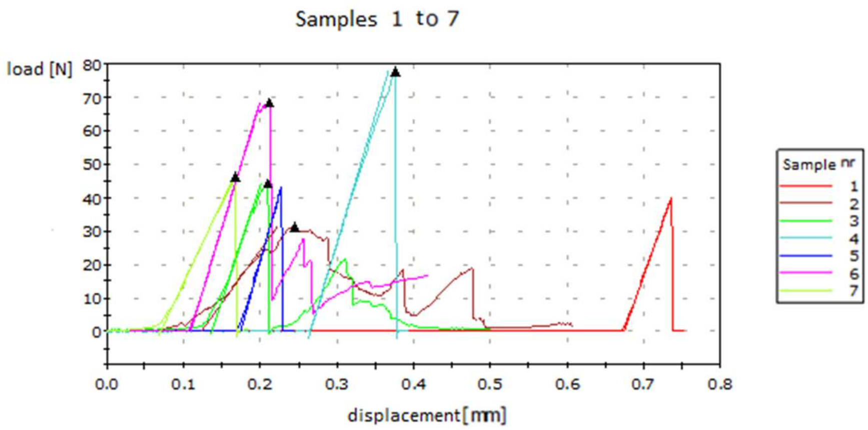

Fig. 8. The dependence of the load on the movement of all samples on the enamel after the treatment with a bit

Table 3. Values for samples on the surface of the enamel after laser treatment

Lp.	Sample label	Maximum load F [N]	Maximum tangential stress τ_{max} [MPa]
1	sample_1	26,51	8,44
2	sample_2	27,59	8,78
3	sample_3	26,92	8,57
4	sample_4	60,34	19,21
5	sample_5	29,17	9,28
6	sample_6	17,07	5,43
7	sample_7	57,66	18,35
Average		35,04	11,15
Standard deviation		16,85	5,36

Average tangential stress maximum with uncertainty for the enamel after laser treatment:

$$\tau_{max_{śr}} = 11{,}2 \pm 5{,}7 \quad [MPa]$$

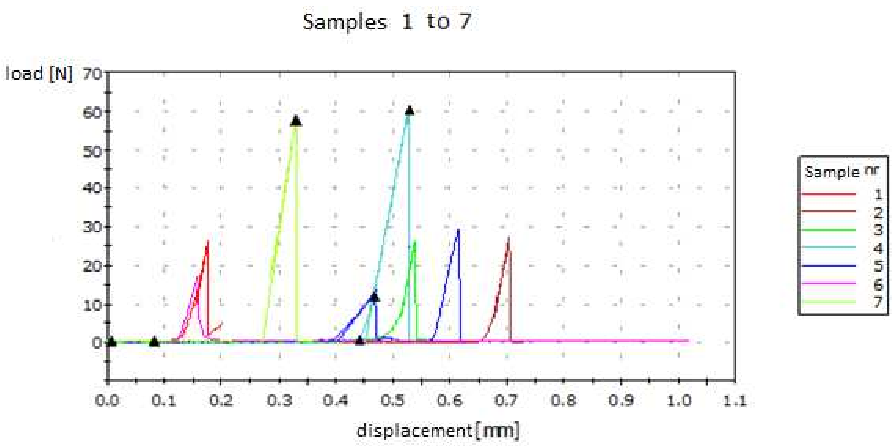

Fig. 9. The dependence of the load on the movement of all samples on the glaze after laser treatment

Development of results

The maximum stress values for three enamel surface conditions were compared:

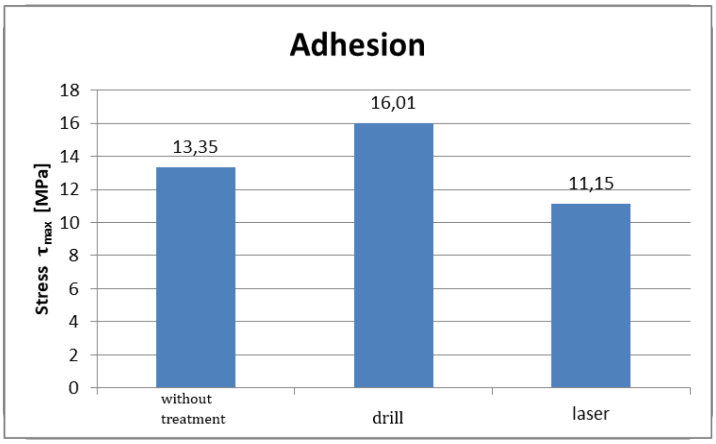

Fig. 10. Adhesion of the enamel composite a) without treatment b) after treatment with a drill, c) after laser treatment

10. CONCLUSIONS

1. It has been shown that the tooth surface condition has a significant effect on the adhesion strength of the composite to the enamel.
2. The highest load values were found to be sustained by specimens after machining with a drill (Fig. 10), then glazed specimens without processing, and glaze samples after laser treatment were able to transfer the smallest loads.
3. It can be concluded that the greater the roughness, the stronger the adhesion force in the joint will be.
4. Differences in the strength of adhesion were also caused by differences in the enamel structure, because the elemental composition and hardness depend on genetic conditions and oral hygiene of each person. A significant difference can be seen in the results and the load and displacement graph for the glaze-free composites (Fig. 10).
5. The uncertainty of measurements was influenced by errors in the alignment of the sample in the measuring machine. The offset of the composite by a small angle could give completely different results for the shear force. Normal stresses were not included in the experiment.
6. In all the samples, the composite was detached entirely from the enamel surface. Therefore, it is important to properly prepare the surface and use a good quality intermediate layer.
7. The most reproducible results were obtained for samples with enamel after laser treatment, however, due to 2 measurements deviating from the rest, the calculated standard deviation turned out to be greater than the enamel samples after the treatment with a bit.

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WPŁYW STANU POWIERZCHNI NA ADHEZJĘ MATERIAŁU KOMPOZYTOWEGO DO SZKLIWA

Praca przedstawia metodę pomiaru maksymalnego naprężenia jakie wytrzyma próbka kompozytu umocowana na powierzchni zęba. Badanie przeprowadzono dla 3 różnych stanów powierzchni szkliwa: bez obróbki, po obróbce wiertłem diamentowym oraz po obróbce laserem diodowym. Siłę adhezji zmierzono w maszynie wytrzymałościowej Instron 5960. Wyniki potwierdzają znaczący wpływ stanu powierzchni na adhezję kompozytu do szkliwa.

Słowa kluczowe: maszyna wytrzymałościowa, obróbka zębów, laser, wiertło stomatologiczne.

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Andrey VARLAMOV[1]
Zheng ZHOU[2]
Yan CHEN[3]

BOILING, STEAMING OR RINSING? (THE PHYSICS OF CHINESE CUISINE)

Some physical aspects of Chinese cuisine are discussed. We start from the cultural and historical particularities of Chinese cuisine and their food production technologies. What is the difference between raw and boiled meat? What is the difference in the physical processes of heat transfer during either the steaming of dumplings or during cooking them in boiling water? Why is it possible to cook meat stripes in a "hot pot" in ten seconds, whilst baking a turkey requires several hours? This article is devoted to a discussion of these questions.

Keywords: complex organic molecules, proteins, damplings, heat transfer, temperature conductivity, Fourier law, Newton's law of cooling

Globalization, which is rapidly taking place throughout the world, is vividly manifested by the ubiquitous availability of dishes of various cuisines from all over the world. Of course, as a rule, these have only some semblance of the true masterpieces of culinary art: in addition to the skill of the cook, the creation of the latter requires the corresponding products. As our familiar Italian gastronomic critic, Sergio Grasso, says, "food does not go to a person, this person should travel to food."

Chinese cuisine is one of the richest and most interesting cuisines in the world. Here everything, or, well, almost everything, can be eaten. And the ways of cooking are very different. One of the authors (AV) had a chance during a visit to Shanghai to open a small door into this wide world and, under the guidance of the two other authors, make some first steps in it, being interested not only in the exotic tastes but also in the underlying unusual physical processes.

Speaking about Chinese cuisine, the first things that come to mind, probably, are the dumplings, worldwide the most popular Chinese dish, which you can eat in Chicago, Canberra, or Moscow. Dumplings are honoured all over China, especially in Jiangnan region of China (close to the Yangtzi Delta). Three types of dumplings are commonly seen, especially in Shanghai and Suzhou, namely,

[1] Andrey Varlamov, CNR-SPIN, Viale del Politecnico 1, I-00133 Rome, Italy
[2] Zheng Zhou, Department of Physics, Fudan University, Shanghai, China
[3] Yan Chen, Department of Physics, Fudan University, Shanghai, China

Siaulon Pau, ***Santsie Moedeu*** and ***Wonton***. Made of a thin dough, filled with pork, the fat of which melts into the soup when cooked, and served with Chinkiang vinegar, they are all pretty much the same. The most significant difference is the method of their heat treatment. ***Santsie Moedeu*** (large size dumpings) are pan-fried, this process is called in Shanghai ***"Santsie***". ***Wonton*** dumplings are boiled in 100°C, whereas ***Siaulon*** dumplings are processed also at 100°C, but in an atmosphere of saturated steam in small bamboo steaming baskets which are called ***"Siaulon"*** (see Fig. 1).

Fig. 1. The three kinds of dumplings in Jiangnan, China. The left one is Santsie Moedeu, the middle one is Siaulon Pau and the right one is Wonton

Hotpot is also a popular type of Chinese cuisine. Originating in Mongolia more than 1,000 years ago and gaining its popularity in the times of the Qing Dynasty[4] all over the country, hotpot boasts a profound history. During its spread, hotpot was diversified into many variations. ***Beijing hotpot*** lays particular emphasis on the soup base and sauces, ***Chongqing hotpot*** boasts a stimulating and refreshing "*Ma La*" ("麻辣", "numb and spicy") flavor, and ***Chaoshan hotpot*** is famous for its deliberately-prepared thin-cut mutton, named "*Shuan Yangrou*" ("涮羊肉") in Chinese.

When enjoying hotpot, one puts ingredients such as beef balls, fish balls, crab meat, or vegetable slices into the elaborately prepared soup base and waits for it to be done. After picking it up and dipping it in the sauce, delicious food is ready to eat. The whole process is called "*Zhu"* ("煮", "to boil") in Chinese, and takes 5-10 minutes or so, when applied to meat balls or vegetables. Remarkably, in the meantime, another process can be used to get a different kind of food in the same hotpot, but much quicker. In Chinese it is called ***"Shuan"*** ("涮", "rinse" or "instant-boil"). It consists of soaking the thin-cut sliced beef or mutton in the boiling soup. Surprisingly in only 10 seconds the sliced beef changes it colour

[4] The Qing dynasty was the last imperial dynasty of China, established in 1636 and ruling China from 1644 to 1912 with a brief, abortive restoration in 1917. It was preceded by the Ming dynasty and succeeded by the Republic of China.

from pink to white or gray, indicating that the slice is ready to eat. The beef slice becomes ready even without being let go of by the chopsticks (see Fig. 2).

Fig. 2. Cooking in the hotpot

Today, cooking has become not only a giant industry, not only an art, but also a vast field of science. Here, biology, chemistry, physics, economics, ethics and many more intersect. The tasks of this science are infinite. All the time, new methods of cooking appear. We will not even try to list them here – neither those for the frying of meat, nor those for baking turkey, nor even the preparation of a BBQ on charcoal, none of them will be discussed here. Instead let's talk about the physical processes underlying cooking in the examples of the dishes described above - about the physics of boiling, steaming, and “rinsing in hotpot”.

Boiling

What is the essence of the process of boiling meat? In everyday language, raw meat should become cooked. And what does this mean "scientifically"?

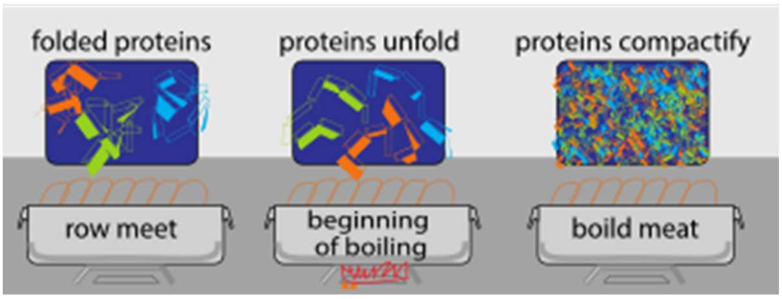

Fig. 3. Protein denaturation

Meat, basically, consists of complex organic macromolecules called proteins (the type of protein varies depending on the type of meat). In raw meat, the protein molecules are in a state of long entangled chains (Fig. 3). In the course of heat treatment, the temperature rises and these chains straighten, and when the temperature reaches value T_d, specific for each type of meat, they are compactified into a kind of "carpet". This process is called protein denaturation. It occurs at relatively low temperatures: for meat it is 55~80°C, and for fish the temperature is even lower. In any case, anyone who has ever eaten a chicken soup can be sure that boiling it at 100°C turns out to be sufficient for completely compacting the proteins in the meat.

From the point of view of physics, the states of proteins in raw meat and boiled meat differ in their energy.

To turn the protein from its native state to the denaturated one, an energy barrier must be overcome (Fig. 4). At room temperature, this barrier is high. In the process of cooking, the temperature rises. Correspondingly the energy of the protein changes, as is shown in Fig. 4. Having reached the top of the "hill", the protein falls down to the new state – a denatured protein – the meat is cooked! This is what happens in a pot of boiling soup.[5]

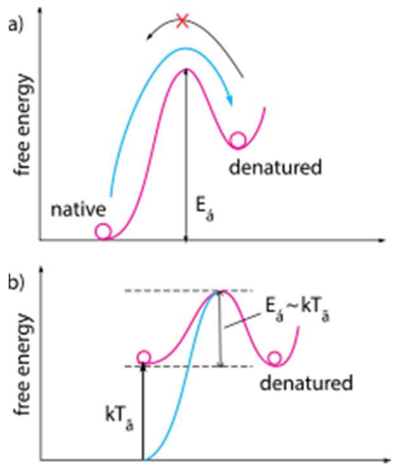

Fig. 4. A schematic presentation of the process how protein overcomes the energy barrier when the temperature increases

So, the first task of the cook when boiling meat in terms of physics is to increase the temperature throughout the volume of the piece to at least the temperature of denaturation.

[5] It should be noted that in recent years became fashionable to cook meat at relatively low temperatures, the so-called "sous-vide" method. The meat is placed in a thermostat with a temperature somewhat lower than that of denaturation. Each separate macromolecule lack energy alone to jump over the barrier. However, it can occasionally "borrow" it from the environment. So, gradually (it takes a long time - many hours, maybe even a day), all bulk of the meat transfers into the denaturated state.

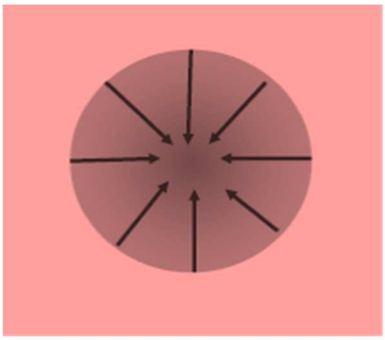

Fig. 5. Penetration of heat in the spherically symmetrical piece of meat

In the light of the above, we formulate the simplest model of the process of meat cooking. Let a spherically symmetric homogeneous piece of meat (radius R) with an initial temperature T_0 and a thermal conductivity coefficient κ be placed in an environment where a fixed temperature T_e is maintained. How much time does it take for the temperature of the meat in the center of the ball to reach T_g? (Fig. 5)

In mathematical physics, the process of heat transfer inside a sphere is described by a complicated differential equation [1]

$$\frac{\partial T(r,t)}{\partial t} = \frac{\kappa}{\rho c}\frac{\partial}{\partial r}\left(r^2 \frac{\partial T(r,t)}{\partial r}\right) \tag{1}$$

where $T(r, t)$ is the temperature at a point r at time t, κ is the thermal conductivity of the meat, ρ is its density, and c is the specific heat. Since the water is boiling in a saucepan, the temperature at the surface of the sphere at any instant of time remains constant and equal to 100°C

$$T(r = R, \forall t) = 100℃ \tag{2}$$

We took the meat from the refrigerator, so at the time when it was dropped into the water, the temperature was 4°C throughout its volume:

$$T(\forall r, t = 0) = 4^{\circ}\mathrm{C} \tag{3}$$

Equations (1)-(3) determine the problem of a differential equation with boundary conditions. How to deal with them is well known for mathematicians, and knowing the numerical values of the thermal conductivity of meat, its density and specific heat, they will be able to accurately write a recipe for cooking broth.

Nevertheless, let's try to figure out the answer by ourselves using the method of dimensional analysis. The temperature of denaturation of meat is the same order of magnitude as the boiling point of water (it differs from it by only 20~25%). Therefore, we assume that the time of "delivery" of the necessary temperature to the center of the solid sphere depends only on its material parameters: the thermal conductivity of the meat, its density, specific heat and radius. Therefore, we seek the dependence of the required time on the size of the sphere in the form:

$$\tau = \kappa^{\alpha}\rho^{\beta}c^{\gamma}R^{\delta} \tag{4}$$

By comparing dimensions, we write:

$$[\tau] = [\kappa]^{\alpha}[\rho]^{\beta}[c]^{\gamma}[R]^{\delta} \tag{5}$$

The dimension of the thermal conductivity is $[\kappa] = (\mathbf{kg}\cdot\mathbf{m})/(s^{3}\ \cdot {}^{\circ}\mathbf{C})$. Substituting this and the dimensions of all the other physical values into equation (5), and then comparing them on the right and left hand side, we find: $\alpha = -1$, $\beta = \gamma = 1$, $\delta = 2$. Thus, we conclude that

$$\tau = C_0\frac{\rho c}{\kappa}R^2 \tag{6}$$

Where C_0 is an unknown constant of the order of unity. Substituting the quantities $\kappa = 0.45\ \mathbf{W}/(\mathbf{m}\cdot{}^{\circ}\mathrm{C})$, $\rho = 1.1\times10^{3}\ \mathbf{kg}/\mathbf{m}^3$, $c = 2.8\ \mathbf{kJ}/(\mathbf{kg}\cdot{}^{\circ}\mathrm{C})$, we find that for the meat $\chi = \kappa/\rho c = 1.5\times10^{-7}\ \mathbf{m}^2/\mathbf{s}$. This value is called the coefficient of temperature conductivity. Consequently, a half kilogram piece of meat should be cooked for about an hour and a half. The estimate is in some way exaggerated, since we do not distinguish here the temperature of denaturation from the boiling point of water, but the order of magnitude is correct.

Returning to the dumpling whose diameter is about 2 cm, we find that it should be cooked for several minutes, which corresponds to our life experience.

Steaming

Now let's discuss the physical aspects of the preparation of *Siaulon* dumplings. Here, a meat ball of radius R (our model of the dumpling) is placed into an atmosphere of saturated steam at 100°C. The pressure here is atmospheric pressure, i.e. equal to 1 atm. Formally, the *Siaulon* dumpling can be considered here as under the same boundary conditions as the *wonton* dumpling in the boiling water. Indeed, it is taken from the same refrigerator and is placed into an environment with a temperature of 100°C. Therefore, from the point of view of a mathematician, the propagation of heat in the *Siaulon* dumpling is described by the same equation (1) with the boundary conditions (2) and (3). Therefore, if condition (2) is satisfied, then the temperature distribution inside it will be the same as for the *wonton* dumpling of the same size, and its preparation should take about the same time. However, a physicist is obliged to answer: how is one to ensure a temperature of 100°C on the surface of the *Siaulon* dumpling?

In the case of a "wonton" this was easy: even though immediately after its placement in the pan the boiling around it temporarily terminates. Due to the high heat capacity of the water, its good heat conductivity, convection, and the constantly supplied heat to the pan, the water will very quickly boil again thus providing condition (2) and hence, the required heat flow into the dumpling.

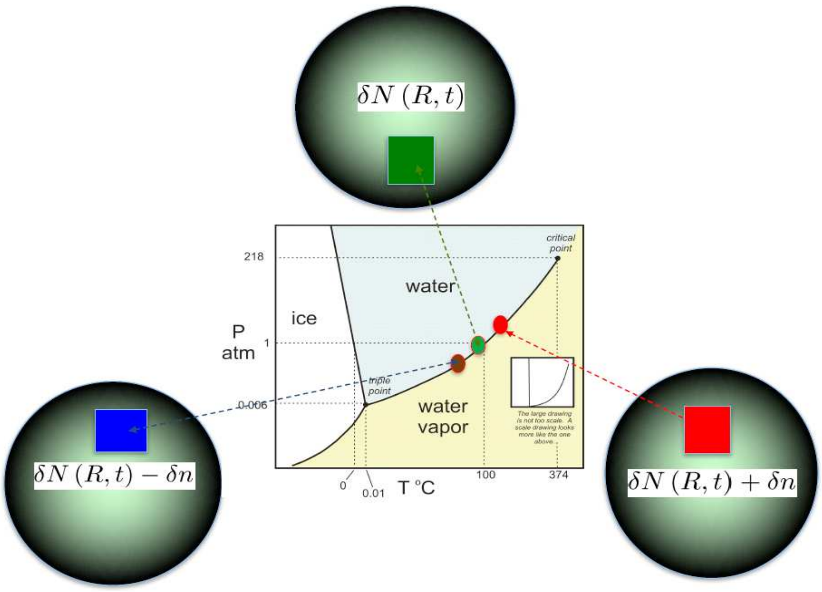

Fig. 6. A schematic representation of the process of dumpling steaming in the phase diagram of water. The environment ensures not only the heat flow but also the negative feedback suppressing its fluctuations

In the case of the "Siaulon", cooked in an atmosphere of saturated steam, the mechanism of the heat transfer into the dumpling is not so evident. How in this case is the boundary condition (2) ensured. Here the heat transfer has a completely different character from the one discussed in the previous section. At the first moment, the vapor molecules near the still cold surface of the "Siaulon" are locally in the state of a strongly supersaturated vapor. They begin to condense on the surface rapidly increasing its temperature up to the ambient temperature, 100°C (Fig. 6). Assuming that the temperature jump occurs in a very narrow region close to the surface, we return to the same equation (1) with boundary conditions (2) and (3). I.e., the temperature distribution inside the "Siaulon" should change with time in the same way as in the case of the "Wonton" boiled in the water. Consequently, the heat flux[6]

$$q(R,t) = -\kappa \left[\frac{\partial T(r,t)}{\partial r}\right]_{r=R} \tag{7}$$

at its surface should be the same. Yet, now this flow is provided not by the thermal conductivity of the water, but by the molecules of the vapor “landing” on 1cm^2 of the surface during 1 second:

$$q(R,t) = \Gamma\, m(t) = \Gamma\, \frac{\mu_{\mathbf{H_2O}}}{N_A} N(t). \tag{8}$$

Here Γ is the specific heat of evaporation, $N(t)$ is the number of molecules condensed per second, $m(t)$ is their mass, N_A is the Avogadro number, $\mu_{\mathbf{H_2O}}$ is the molecular mass of water. Thus, the number of molecules "landing" from the steam atmosphere on a square centimeter of "Siaulon" per second is

$$N(t) = N_A \frac{\kappa}{\Gamma \cdot \mu_{H_2O}} \left[\frac{\partial T(r,t)}{\partial r}\right]_{r=R} \tag{9}$$

Perfect! Mathematicians can find this number by solving the complicated equation, the "Siaulon" itself "feels" what heat flux it needs to keep the temperature at 100 ° C on the surface ... It remains only to understand from where the molecules of the vapor learn how many of them should condense in a given second at a square centimeter of the "Siaulon” surface.

Let's suppose that at some time $N(t) + \delta N$ instead of $N(t)$ molecules condense. The first $N(t)$ of them are hospitably absorbed by the “Siaulon” – in fact, they are necessary to keep in harmony a centigrade surface and still a cold inner part. The remaining δN are persons “*non grata*” – they were not expected here, the temperature conductivity of the “Siaulon” does not allow their heat released

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[6] A basic way for heat to enter the substance is thermal conduction [2,3]. When two objects with different temperature are in contact, heat flows from the one with high temperature to the one with low temperature. A basic model to study thermal conductivity is a slab of material of thickness.
The rate of thermal conduction is measured by the heat flux density, which is the amount of heat
睸_睼_穄_穆_麋_窐_窒_窔_
Experimentally, and inversely proportional to the length. The coefficient is written in the gradient. The equation above is called “Fourier’s law”.

to penetrate into the dumpling. What do they have to do? To take off again? Too troublesome, so they stay on the surface locally increasing its temperature (see Figure 6). As a consequence, the point that represents the local balance of the vapor and water moves up along their coexistence line. Let us notice that the pressure in the system remains the same, equal to 1 atm. Therefore, above the selected square centimeter, the vapor locally ceases to be saturated. As a result, the next moment there will land somewhat fewer molecules than the required amount. Consequently, the surface temperature will go down.

Exactly the same mechanism works also in the case of that fewer than the required number of molecules condense onto the surface per second than would return the temperature back to 100°C (see Fig. 7). Such a mechanism of self-regulation is called negative feedback.

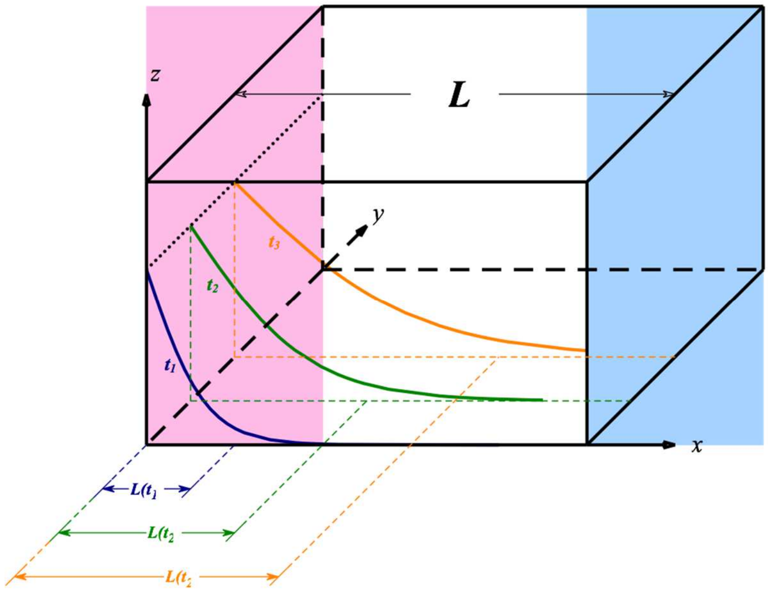

Fig. 7. A schematic of temperature penetration into a semi-space

Let us note the important culinary difference between boiling and steaming of dumplings. In the former case water penetrates into a dumpling due to the diffusion process. Interacting with its filling it creates a tasty juice. Due to the same diffusion, but in the opposite direction, this juice partially flows out from the dumpling to the surrounding liquid, transforming the water into a diluted broth. In the case of steaming the dumplings the ambient environment is the saturated steam. Once condensed at the surface of a dumpling the water also diffuses into its bulk, but there is no inverse process. Hence, the juice of the steamed dumpling is richer than that of the boiled dumpling.

Rinsing

At the beginning of this article we discussed the "hot pot" and the different ways of cooking meat in it. Yet there still remains the mystery as to why the same amount of meat in the form of a meatball or a thin slice differs in its cooking time by up to ten times. Why the oil soup base "Hongyou" in the Chongqing pot boils much earlier than the water soup "Qingtang" used in its Chaoshan and Beijing versions? We will try to answer these questions below.

On cooking times

"Shuan" and "Zhu" is actually the same thermal process which was discussed in the previous sections. Here heat conductivity and convection provide a constant temperature 100°C on the surface of the object and heat enters inside it, raising the internal temperature. So, what causes this striking difference in time between rinsing the thin-cut beef and boiling the meatball? The answer requires an inspection of the thermal process of boiling.

With the time of "Zhu" everything is clear: the way of heat propagation in the ball, which can serve as a meatball model, we already discussed (cooking of the Wonton dumpling**)**, and we can use Eq. (6) to estimate the corresponding time. The cooking time of the "Shuan" process requires separate consideration.

We consider a body occupying the semi-space $x > 0$ (see Fig. 7) We assume its density, heat capacity, and heat conductivity to be ρ, c, κ , and with a temperature T_0 at the initial moment $t = 0$. Now let us change the temperature at its surface $x = 0$ to T_1 and fix it. Fig. 7 shows how the temperature evolves with time in the bulk of the body. We can see that heat penetrates into the medium little by little. One can introduce characteristic length $L(t)$ to describe the propagation of the temperature front with time. Returning to Fourier law (see Eq. (9)) and replacing the thickness Δx by the characteristic length $L(t)$, substituting $Q = mc\Delta T$, and $m = \rho A L(t)$, one finds

$$\frac{c\rho A L(t)\Delta T}{At} = \kappa \frac{\Delta T}{L(t)}$$

Solving this equation with respect to $L(t)$

$$L(t) \sim \sqrt{\frac{\kappa t}{c\rho}} = \sqrt{\chi t} \ . \tag{10}$$

Solution of the exact differential equation describing the process confirms our qualitative consideration [4] and gives an extra $\sqrt{\pi}$ coefficient in (10):

$$L(t) = \sqrt{\pi \chi t}$$

Hence, we found that heat penetrates into the medium by the square-root law of time, the parameter $\chi = {}^{\kappa}/_{c\rho}$ is called the thermal diffusivity or coefficient of temperature conductivity[7]. The time of the establishment of the temperature $\mathbf{T_1}$ in the slab of the thickness L can then be evaluated as $\tau \sim {}^{L^2}/_{\pi\chi}$

Now we can return to a comparison between the rinsing time of a thin-cut beef versus the boiling time of a meatball. We consider an $a \times b$ rectangular slice of thickness d and a meatball of radius R out of the same volume of meat.

During the boiling process, temperature should penetrate into specimen up to the farthest point from the surface. Thus, the required length for thin-cut slices and meat balls are respectively half its thickness and its radius. The times for them to be done are

$$\tau_{\mathbf{slice}} \sim \frac{\left({}^{d}/_{\mathbf{2}}\right)^2}{\pi\chi} \quad \tau_{\mathbf{ball}} \sim \frac{R^2}{\pi\chi} \tag{11}$$

The ratio between their cooking times is

$$\frac{\tau_{\mathbf{ball}}}{\tau_{\mathbf{slice}}} \sim \left(\frac{2R}{d}\right)^2$$

The size of a thin-cut sliced beef in China typically is $a \times b = 3 \times 15\mathbf{cm}$ and its thickness is 1mm, which is marvelously thin. Out of the same volume of beef, using $abd = {}^{\mathbf{4}\pi R^3}/_{\mathbf{3}}$, we can make a beef ball whose radius is $R = 1.0\mathbf{cm}$. The ratio ${}^{\mathbf{2R}}/_{\mathbf{d}} = \mathbf{20}$ and the estimated difference in cooking times is

$$\left(\frac{\tau_{\mathbf{ball}}}{\tau_{\mathbf{slice}}}\right)_{\mathbf{est.}} \mathbf{\sim 400} \tag{12}$$

Stop! As we have mentioned above the common times for the ball and the slice to be cooked are 5 minutes and 10 seconds, i.e. the realistic value for the ratio is

[7] Thermal diffusivity is a physical quantity that describes the rate of change (align) the temperature of the substance in a non-equilibrium thermal processes.

$$\left(\frac{\tau_{\mathbf{ball}}}{\tau_{\mathbf{slice}}}\right)_{\mathbf{real.}} \sim 30 \tag{13}$$

This number differs by an order of magnitude with (11), this is too much. The reason for this discrepancy is our assumption that all of the cooking time is spent on "delivery" of the necessary temperature through the whole volume of the meat. However, we ignored the time required for carrying out the denaturation process itself. In most cases, this time, $\tau_{\mathbf{denat.}}$, is so short that it can be neglected with respect to the "delivery" time. Yet, the "Shuan" process is so quick that the denaturation time cannot be neglected and has to be added to

$$\tau'_{\mathbf{slice}} : \tau'_{\mathbf{slice}} = \tau_{\mathbf{denat}} + \frac{\left(d/2\right)^2}{\pi\chi} \tag{14}$$

where the temperature conductivity of the beef is taken as $\chi_{\mathbf{beef}} = \mathbf{1.5 \times 10^{-7} m^2 s^{-1}}$. The value of the second term in (14) is only $\left(\frac{1}{2}d\right)^2 / \pi\chi \sim 0.5\ \mathrm{s}$, while one rinses it in the hotpot around 10 seconds. It is why we conclude that all this time is required for the chemical reaction of denaturation i.e. $\tau_{\mathbf{denat}} \sim \mathbf{10 s}$. Of course, this value is negligibly small compared with that required to increase the temperature throughout the entire meatball volume above the denaturation point, but it turns out to be dominant when rinsing a slice of meat in a hot pot. The new estimate $\tau_{\mathbf{slice}} \sim \mathbf{10s}$ $\tau_{\mathbf{ball}} \sim \mathbf{220}s$ agrees well with Chinese experience.

Table 1. Comparison among three ways of cooking mentioned above
– boiling, steaming and rinsing

	Boiling	**Steaming**	**Rinsing**
Size	Radius R	Radius R	Thickness $L \ll a, b$
Cooking time	$\tau \sim \mathbf{R^2}/\pi\chi$	$\tau \sim \mathbf{R^2}/\pi\chi$	$\tau \sim \mathbf{L^2}/\pi\chi$
The Way of heat transfer	Thermal conductivity & natural convection	Latent heat of the condensing steam	Thermal conductivity & forced convection
Environment	Boiling water/diluted broth	Saturated steam	Boiling soup-base

On soup bases

Besides the process of boiling sliced beef itself, the soup-base also contains some physics in it. First of all, it differs strongly from the diluted aquatic broth formed during the boiling of dumplings(see above). The soup-base for the hot pot is prepared in advance, mixing water with oil and other ingredients. Below we discuss some of its specific properties which also have interesting physical reasons.

"Qingtang" soup base is commonly used in the Beijing and Chaoshan hotpots. It constitutes a mix of water with a small amount of oil, salt and other condiments. Contrarily, for cooking in a Chongqing hotpot the "Hongyou" (spicy oil) soup base serves. A large fraction of "Hongyou" soup is oil stewed with chili powder, Chinese prickly ash, etc. The remaining part is a small portion of water. If one starts to heat both soups simultaneously, the oil soup-base will start to boil much earlier than the water soup. It seems to be rather strange, since the boiling point of oil (if any) is much higher than that of water. Actually, what boils here is not the oil, but the small portion of water in the soup. Hence, the Hong You soup starts to boil at the boiling point of water instead of that one of oil.

There are two reasons which explain why the "Hongyou" soup needs a shorter time to boil.

The first is that the specific heat capacities of oil and water are respectively $c_{\mathbf{oil}} = \mathbf{2 \times 10^3}\ \mathbf{J}/(\mathbf{kg \cdot {}^\circ C})$ and $c_{\mathbf{water}} = \mathbf{4.2 \times 10^3}\ \mathbf{J}/(\mathbf{kg \cdot {}^\circ C})$, so that less than half the heat is needed to raise the temperature of the oil soup base from room temperature to 100℃.

The second reason concerns heat dissipation. The process of the heat dissipation is due to both heat conduction and convection processes. In the latter energy is transferred by the movement of a heated substance as a result of differences in densities of lower and higher layers.

The heat flux at the surface is loosely described by Newton's law of cooling, which claims that the latter is proportional to the temperature difference: $q = \boldsymbol{h}\Delta T$.

The coefficient $\boldsymbol{h}$ is called the heat transfer coefficient and describes how violent the convection is. The typical values of the heat transfer coefficient for boiling water and oil are respectively $2.5 \times \mathbf{10^3} \sim 25 \times \mathbf{10^3}$ and $0.05 \times \mathbf{10^2} \sim 1.5 \times \mathbf{10^2}$, in units of $\mathbf{W \cdot m^{-2} K^{-1}}$. The significant difference in $\boldsymbol{h}$ may be explained by the viscosity and the poor heat conductivity of oil. As a result, the heat dissipation at the interface between the oil soup and air is two orders of magnitude less than that in the case of water soup.

Manman Chi![8]

[8] 慢慢吃-"eat slowly", Chinese version of "enjoy your meal"

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GOTOWAĆ, GOTOWAĆ NA PARZE CZY MOŻE PŁUKAĆ? (FIZYKA KUCHNI CHIŃSKIEJ)

W artykule zostały przedyskutowane niektóre aspekty kuchni chińskiej. Autorzy zaczynają od omówienia szczegółów kuchni chińskiej i technologii produkcji żywności. Autorzy zadają następujące pytania: jaka jest różnica pomiędzy mięsem surowym a gotowanym? Jaka jest różnica w fizyce procesu przenoszenia ciepła podczas przyrządzania klusków na parze wodnej a w gotującej się wodzie? Dla czego jest możliwe przyrządzanie kawałków mięsa w "gorącym garnku" w ciągu kilku sekund, podczas gdy po to, aby upiec indyka potrzebujemy kilku godzin? Artykuł ten udziela odpowiedzi na te i inne pytania.

Słowa kluczowe: złożone molekuły organiczne, proteiny, kluski, przenoszenie ciepła, przewodnictwo temperaturowe, prawo Fouriera, Newtonowskie prawo chłodzenia

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e-mail: gzyla@prz.edu.pl
tel. +48 17 865 1273

Adres pocztowy i afiliacja Komitetu Redakcyjnego

Politechnika Rzeszowska
Wydział Matematyki i Fizyki Stosowanej
al. Powstańców Warszawy 6
35-959 Rzeszów, Polska

Informacje dla autorów
http://oficyna.prz.edu.pl/zeszyty-naukowe/physics-for-economy

Dane kontaktowe do wydawcy

Kierownik Oficyny Wydawniczej
mgr inż. Joanna BIENIASZ
Politechnika Rzeszowska
al. Powstańców Warszawy 12
35-959 Rzeszów
e-mail: jbie@prz.edu.pl
tel. +48 17 865 1195