DOI: 10.21062/mft.2022.048 http://www.journalmt.com

Analysis of the Welding Process of Steel Pistons of Internal Combustion Engines

Paweł Żurawski (0000-0003-2528-3230)
Doctoral School of Engineering and Technical Sciences at the Rzeszow University of Technology (al. Powstańców Warszawy 1235-959 Rzeszów, Poland. E-mail: zurawskipawel15@gmail.com

The aim of the article is to analyze the friction welding process of steel pistons, due to the small amount of scientific literature on this subject. First, it is necessary to present the design features of steel pistons and their advantages and disadvantages. Then the article analyses it presenst the types of friction welding processes used in the production of pistons of internal combustion engines with the analysis of their differences. It present two basic methods of welding in the production of steel pistons, i.e. friction butt welding and low pressure friction welding. Finally, a proper analysis of the friction welding processes of steel pistons of internal combustion engines is presented. At the end, the conclusions of the analysis are presented and proposals for improving the process are made.

Keywords: pistons, friction welding, process analysis, new technologies of joining materials

1 Introduction

The dynamic development of the automotive industry forces designers and technologists to search for new directions in the development of construction and technology for the production of components for the production of cars. The more and more frequent tendency in the automotive industry to continuously increase engine performance has resulted in the creation of more and more efficient pistons for combustion engines thanks to the use of more and more durable materials, technological treatments and improvement of engine operating conditions. The increase in durability of the pistons of combustion engines was achieved thanks to the change of the material from which the piston is made and the construction of the piston, which was possible thanks to a change in the production technology and a modern production technique, i.e. friction welding [1].

From year to year, forged steel pistons account for an even greater percentage of the total production of pistons in the world. Their specific properties make it possible to reduce exhaust emissions, increase durability and make the structure slimmer. The differences in the properties of steel and aluminum alloys used in the production of pistons of internal combustion engines determine their structures and properties. In aluminum alloy pistons, the walking channel is made of salt cores, while in the production of forged pistons, two blanks are frictionally welded to obtain a cooling channel. The lower one is an alloy steel forging, the upper one is a machined piece of bar. Forged pistons allow for higher pressures, higher operating temperatures and to reduce the clearance between the piston skirt and the engine cylinder.

In the production of steel pistons, basically two types of friction welding are used, i.e. friction butt welding for large steel pistons and friction welding with a low contact force for small steel pistons. The most important difference in the production of pistons is the required pressure during welding and the size and shape of the welding flash. In the case of friction butt welding, we deal with higher clamping forces and a larger flash, curving in the shape of a mustache. This welding flash is located in the cooling channel, but due to the large cross-section of the cooling channel of large steel pistons, its effect on the oil flow is negligible. In small steel pistons with even 3 times smaller cross-section of the cooling channel, these flashes would have a significant effect, therefore the most common is friction welding with low pressing forces. In this welding method, instead of a flash, a barrel-shaped bulge is created, which does not adversely affect the oil flow, even in a small cooling channel. In the butt welding process, most of the energy needed for the welding process to occur comes from the induction coil and the entire process takes place in an atmosphere of protective gases.

2 Methodology

The analysis of the friction welding process of steel pistons of combustion engines has been divided into components of the welding process. In the first place, the structure of steel pistons and their advantages and disadvantages were analyzed. The design parameters of the piston are influenced by the friction welding process. A literature review was made on the design of pistons. Then, a FEM analysis of the stresses of a typical piston is presented in order to determine the stress distribution.

In the second part, the two most common types of friction welding of steel pistons are distinguished, and then a short analysis of these processes is carried out. The low pressure friction welding process is most commonly used in the small steel piston welding process and the friction butt welding process for large steel pistons. For each of these processes, the course of the process was analyzed and the most important process parameters were distinguished. Based on the literature review, the advantages and disadvantages of both welding processes were determined.

In the chapter containing the process of friction welding with low pressure of steel pistons to combustion engines, a visual analysis of the connection was carried out, the macrostructures were tested in the subsequent zones of the weld and the hardness was measured. The same approach was made in the topic of friction butt welding of steel pistons. The visual examination of the welded joint is aimed at determining the quality of the joint as well as the influence of the type of joint on the flow of the cooling medium inside the piston. The macrostructure test, which is a metallographic test included in the destructive test, allows you to verify the quality of the connection. The last analyzed test is the measurement of the hardness of the welded joint, which tells about the quality of the joint and its strength.

Finally, a summary of the analysis was made, along with the definition of guidelines for the selection of the best method of friction welding in the production process of steel pistons of combustion engines. Probable trends in the development of friction welding processes are also outlined.

3 Analysis of the piston structure

The latest trends in the development of pistons for internal combustion engines aim at increasing their economy and environmental friendliness. Increasing the economy of engines is achieved by increasing the overall efficiency. In current designs of internal combustion engines, the overall efficiency exceeds 42%. Unfortunately, it is difficult to obtain much greater airiness due to the fact that the heat generated in the combustion process cannot be fully converted into mechanical work. Heat losses, depending on the engine design, range from 40 to 60%. The short duration of the process causes that a large part of the thermal energy is discharged to the flue gas, and the limited thermal resistance of materials such as the combustion chamber and adjacent elements makes it necessary to discharge the generated heat energy through the cooling system [2].

Obtaining better economic indicators is possible thanks to increasing the mechanical efficiency. The mechanical efficiency determines the amount of friction loss in the movements of mechanisms in the internal combustion engine, amounting to about 70%, while the piston-cylinder system causes ~ 50% of friction losses in the internal combustion engine. The components of this loss consist of the friction force generated at the contact of the piston carrier and the piston rings with the cylinder. The total economy of internal combustion engines is determined not only on the basis of the amount of friction losses, but also the durability and reliability of their operation [3,4].

In order to be able to describe the structure of pistons in combustion engines, the most important structural elements of the piston should be named. Figure 1 shows an example of the design of the piston.

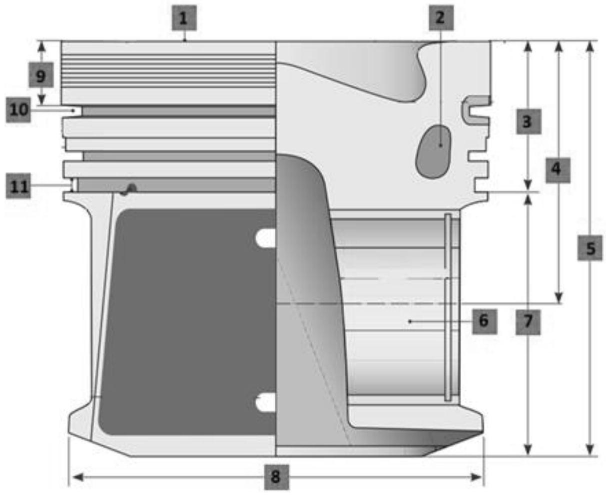

Fig. 1 *Steel piston structure [5]*

Where:
1…Piston crown,
2…Cooling channel,
3…Ring zone,
4…Piston compression height,
5…Piston height,
6…Pin hole,
7…Skirt,
8…Piston diameter,
9…Top lander (fire land),
10…Groove for compression ring,
11…Groove sides.

One of the critical structural elements of the piston are wiper and sealing rings. As for the number of rings, we usually deal with a piston of an internal combustion engine with 3 to 5 pins. Sealing rings separate the combustion chambers from the crankcase, preventing gas blow-by as shown in Figure 2 a. It is the first ring on the piston crown side. On the other hand, the scraper rings are responsible for draining the excess oil from the cylinder surface to the crankcase in such a way as to leave a sufficient amount of oil on its surface, ensuring proper lubrication, thus extending the life of the piston mechanism, as shown in Figure 2 b. Additionally, the piston rings are designed to dissipate heat from the crown and piston walls towards the engine cylinder [6,7].

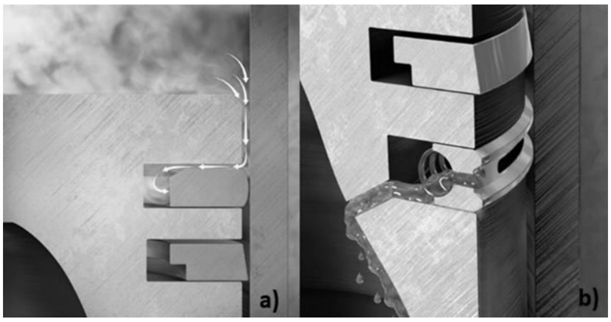

Fig. 2 *a) Isolation of exhaust gases by 1 ring, b) lubrication of the cylinder surface by wiper rings [8]*

The temperature distribution on the surface of the pistons is uneven. The presence of the pin-piston hub and the parts connecting them with the piston crown causes an uneven cross-section. The larger cross-section of these surfaces reduces the thermal resistance and increases the temperature in these regions. For this reason, greater thermal deformation occurs in the direction of the pin axis, which is eliminated by shaping the bearing surface of the piston into an oval shape, with a small oval axis passing through the pin hole axis. Such a shape of the bearing surface causes it to assume a cylindrical shape at the operating temperature [9,10].

During the operation of the internal combustion engine, the piston changes its temperature from the ambient temperature to the operating temperature, which results in a change in the clearance between the piston surface and the cylinder surface. And the value of these clearances also changes with the change of working conditions until reaching the warmer equilibrium state. Fluctuations in the value of these clearances are not only undesirable but are even detrimental to the life and operating conditions of the engine. The value of the clearance affects not only lubrication and friction, but also increases the dynamic load, vibrations and engine noise. [11,12].

Care for environmental protection, reduction of operating costs and production shapes, and increased reliability determine the necessity to conduct development works on new designs of internal combustion engines. Since the cooperation of the elements of the piston-cylinder system is important for the efficiency of the engines and their durability, the improvement of the combustion engine structure is accompanied by an increasingly deeper understanding of the phenomena of lubrication and wear of elements during the operation of the piston-cylinder group [13]. The reduction of friction losses improves the mechanical efficiency of the engine and thus reduces the amount of fuel consumed. In the latest design solutions of internal combustion engines, the friction force of the piston and piston rings is responsible for the greatest amount of losses [14].

During the operation of an internal combustion engine, the piston crown surfaces come into direct contact with the working medium in the engine's working chamber. In this chamber, as a result of the combustion of the fuel-air mixture, it emits a temperature of up to 2000 ° C. The effect of such high temperatures on the piston crown is a heat exchange which occurs by transfer. The heat exchange itself between the piston head and the working medium takes place periodically [15]. Figure 3 shows a typical temperature pattern on pistons of the petrol and diesel engine.

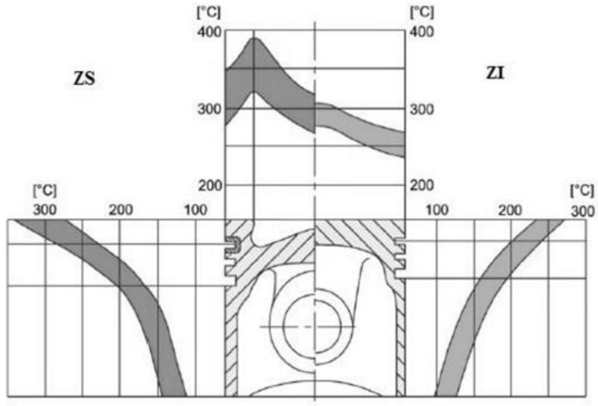

Fig. 3 *Typical temperature distribution on the pistons of the petrol and diesel engine [15]*

The harsh operating conditions of pistons require that specific requirements for the piston materials of internal combustion engines be met. The most commonly used materials for the production of pistons are aluminum alloys, alloy steels and cast iron. In order to reduce the thermal expansion coefficient in the production of aluminum pistons, pistons made of alloys with a high silicon content are used, and the hardness value is increased by heat treatment. In recent years, there has been a noticeable tendency to use alloy steels for the production of pistons due to higher strength and thermal expansion rates. Steel pistons, despite their greater density, are equal to the total weight of aluminum pistons. This is because alloy steel pistons have similar strength with smaller sections. Figures 4 show a comparison of the height of a steel and aluminum piston [2]. Most passenger engines work at peak pressure in the cylinders in the range of 17-19.5 MPa. It is a logical step for car manufacturers to increase this pressure in order to reduce CO in the exhaust gas and improve thermal efficiency. Increasing the pressure to the level of 21-23 MPa gives satisfactory results. This pressure is beyond the strength limit of aluminum pistons, which is why steel pistons with higher strength are more and more often found in new designs of internal combustion engines [16].

Figure 5 shows a comparison of the frictional power of aluminum and steel pistons as a function of oil temperature. A comparative analysis of the friction power showed a reduction of the friction power by about 6% of steel pistons in relation to aluminum pistons.

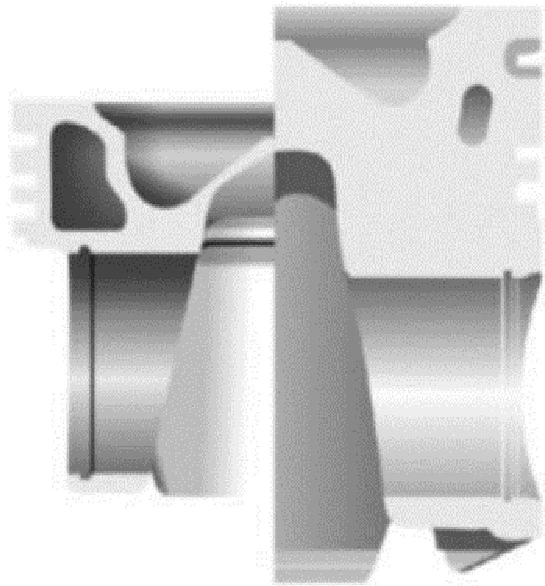

Fig. 4 Comparison of the height of the aluminum and steel piston [15]

The desire to increase the degree of workload of internal combustion engines leads to situations in which engine pistons operate at the limit of permissible loads. This forces engine designers to use materials other than the most commonly used aluminum alloys. An example of such materials is alloy steel. Pistons made of various alloy steels have been made for many years for truck engines, but in recent years the use of this material in the production of pistons for internal combustion engines of passenger cars has been growing [2].

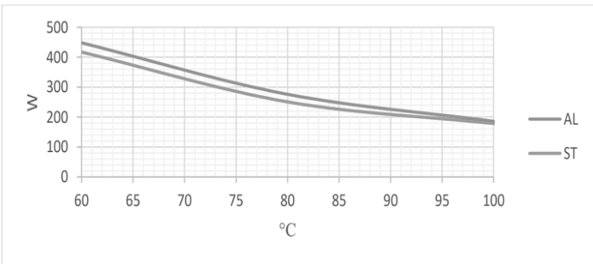

Fig. 5 Comparison of the frictional power of steel and aluminum pistons as a function of oil temperature [17]

One of the first manufacturers to use steel pistons in passenger cars are Mercedes-Benz, BMW and Fiat [17]. Figure 6 shows a cross-section of a steel piston used in passenger car engines. In this drawing, it is worth paying attention to the cooling channel of the steel piston. In the production of aluminum pistons for passenger car engines, the cooling channel is made by the technology of lost models. The salt core is poured with liquid aluminum alloy and then rinsed out. In the production of steel pistons, this is not possible because the piston is made of two parts. Therefore, the cooling channel is made by machining the upper part and the lower part of the piston and then the parts are joined together by friction welding.

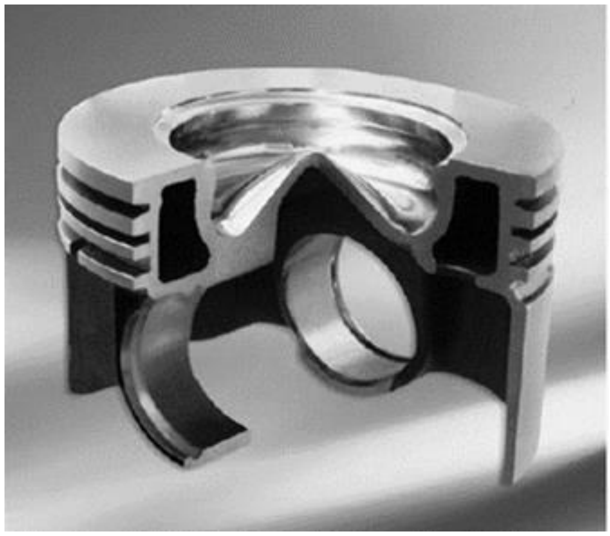

Fig. 6 Cross-section of a steel piston of a passenger car [18]

One of the main features of steel in the production of pistons is the low value of the thermal expansion coefficient. In steel pistons for passenger cars, the cooling channel is relatively larger than in their aluminum counterparts, thanks to which it protects the ring parts against excessive temperature influence, directing it towards the lower and upper part of the combustion chamber. This effectively lowers the temperature of the ring grooves in relation to aluminum pistons. The presence of high temperature negatively affects the strength of the piston. Steel pistons are more resistant to operation at high temperatures than aluminum pistons.

With a comparable weight of steel and aluminum pistons, the contact surface of the steel pistons with the cylinder surface is smaller, thus limiting friction losses. In addition, the lower expansion of steel in relation to aluminum allows for a greater clearance in the piston, reducing the interaction between the piston and the cylinder surface. This is because the lower expansion of the steel causes the contact of the steel piston with the cylinder to be smaller. It is shown in the Figure 7.

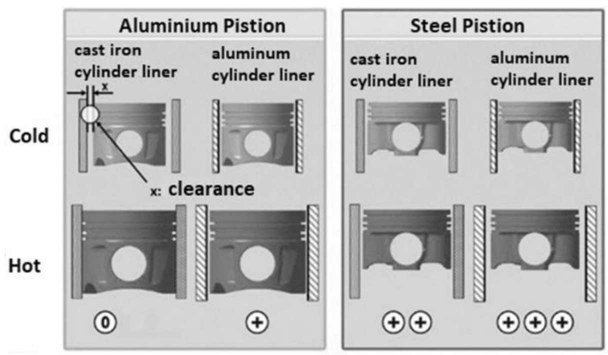

Fig. 7 Diagram of aluminum and steel piston operation under start conditions and during warm-up [20]

Steel pistons dissipate heat less efficiently, which contributes to an increase in temperature on the surface of the combustion chamber in relation to the equivalents of aluminum pistons, which in turn increases the thermal efficiency of the combustion engine, reducing CO, HC and PM emissions. Figure 8 shows the temperature gradient distribution of the combustion chamber of a steel and aluminum piston. The larger cooling channel in the piston promotes the dissipation of heat from the ring grooves, increasing the service life of the pistons. Computer analyzes are commonly used in the analysis of piston structures.

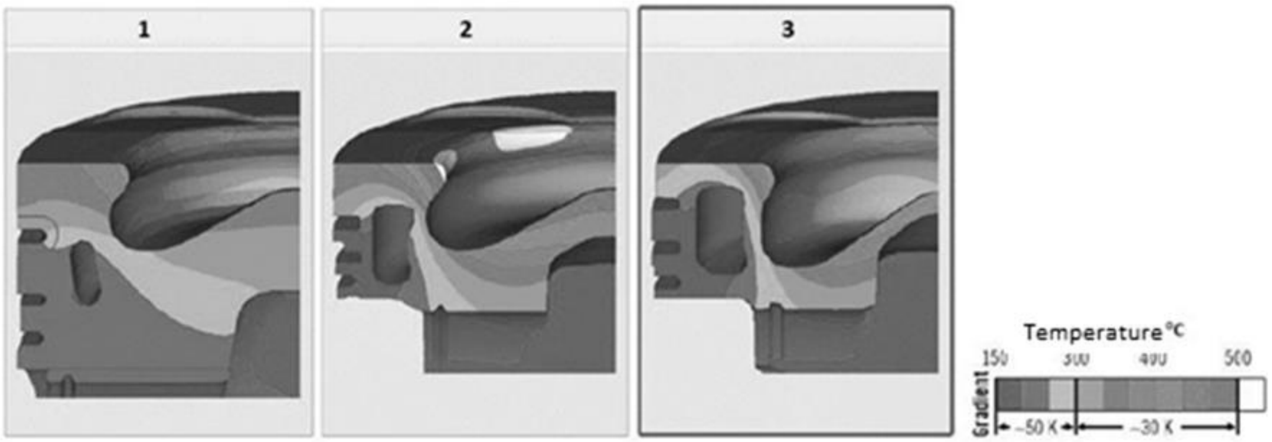

Fig. 8 *Temperature gradient distribution for: 1- aluminum piston, 2-steel piston, 3-steel piston with enlarged cooling channel [20]*

Internal combustion engine pistons are subject to mechanical as well as thermal and mechanical damage. These damages can be divided according to the area of their occurrence into damages: on the piston crown, in the ring grooves, in the pin bore, on the tails, on the piston skirt. Figure 9 shows a typical piston stress distribution. The greatest stresses occur in the area of the piston crown and the base of the pin bore.

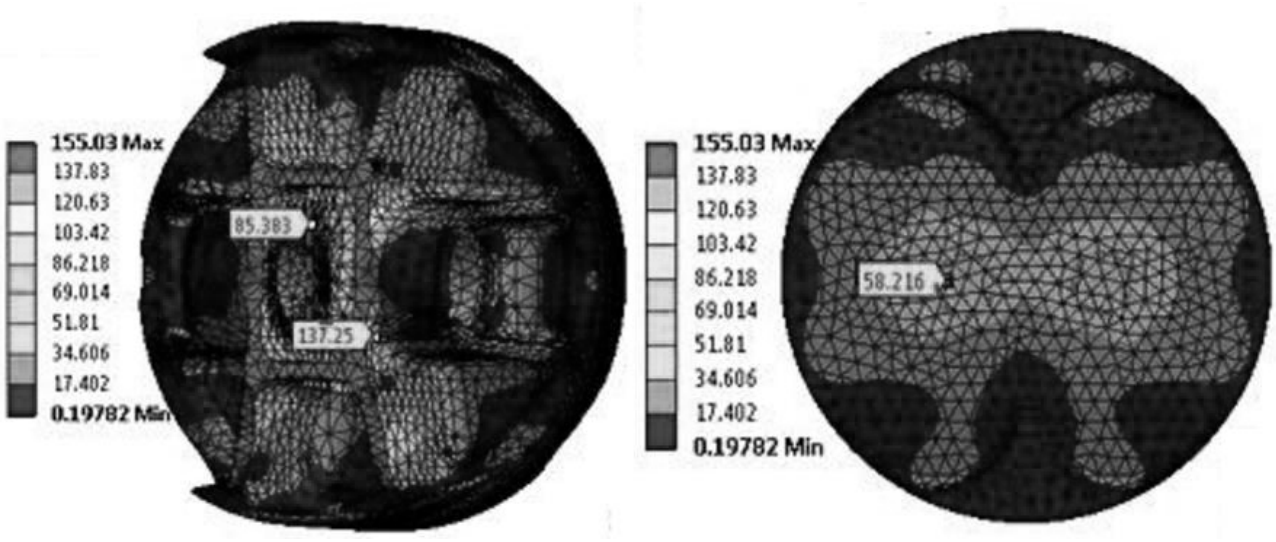

Fig. 9 *Computer analysis of piston stresses in an internal combustion engine [21]*

Another area subject to fatigue failure is the piston ring grooves. Figure 10 shows simulations of von Mises stresses in the grooves of the piston rings. The simulation shows that the greatest stresses occur on the groove radius when the ring is in the middle of the groove depth. The stresses decrease as the ring moves towards the bottom of the groove. This means that the increase in stress on the piston groove increases with the increase in clearance between the piston and the cylinder. Annular grooves are one of the critical parts of the piston with numerous technological limitations.

Another common fatigue failure of pistons is skirt fracture. Figure 11 shows simulations of the piston stress in the skirt area. The simulation shows that the stress concentration in this area occurs near the radius of the skirt curvature. During operation, the piston does not only move up and down. This is because there is play between the piston and cylinder. This clearance causes that during the operation of the piston in the up-down movement, the piston tilts by a certain angle in relation to the cylinder wall, as shown in figure 12. It follows that the piston makes contact in two places during operation. The first is the bottom side of the piston skirt on one side, the second is the top side of the piston.

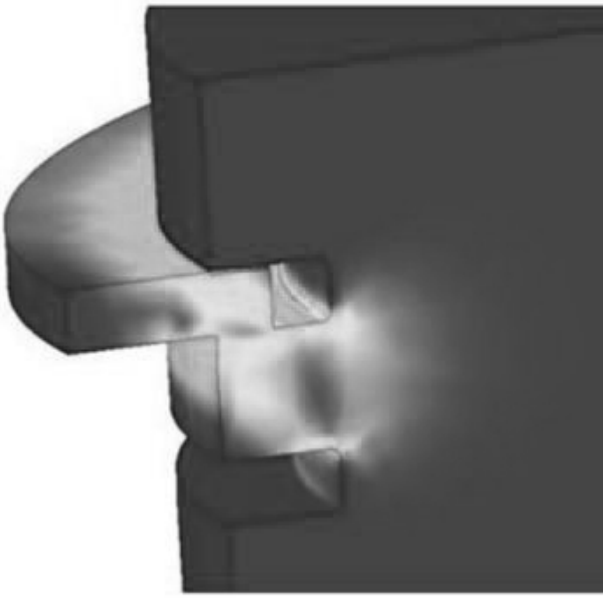

Fig. 10 Stress distribution in the piston groove [21]

Fig. 11 Computer analysis of stresses in the area of the piston skirt [21]

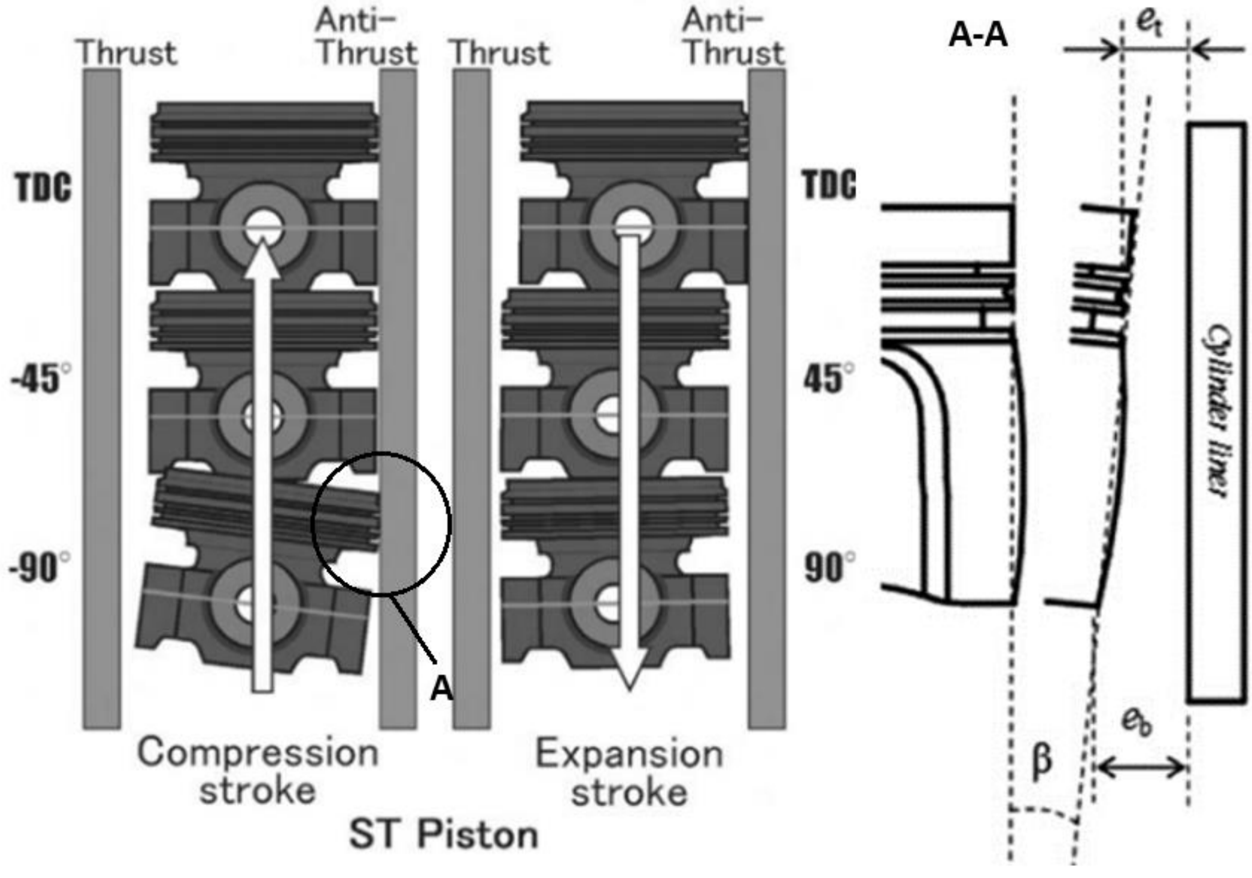

Fig. 12 Diagram of the deflection of the piston during operation [22][23]

4 Analysis of the friction welding process

The friction welding process is a process of joining two blanks known from the last century, when in 1891 the first patent was published in England describing the process of joining two blanks using the heat of friction. Since then, numerous studies have been conducted in many countries around the world in order to use the new method industrially and to optimize it. The advantage of friction welding are the technical and economic benefits, such as: the possibility of joining various materials, process efficiency, the possibility of automation, process stability. Friction welding enables easy joining of materials with high reliability of the connection. The process of solid-state joining is based on bringing the atoms of two joined materials closer together at a distance of the order of the parameters of the crystallographic lattice. This approximation allows for the interaction of atoms to occur on the surfaces of the materials to be joined. The increase in temperature and the pressure force applied to the joined elements facilitates the process of approaching the distance of the interaction of atomic forces between ions, atoms and molecules. This also shows that the friction welding process is considered in the system of temperature and clamping force parameters, as shown in the diagram in Figure 13. This diagram is divided into three zones, of which only in zone II the welding process takes place. In zone I, very high pressing forces are needed for the process to occur, and in zone III, under the influence of high temperature, we deal with liquid metal [25].

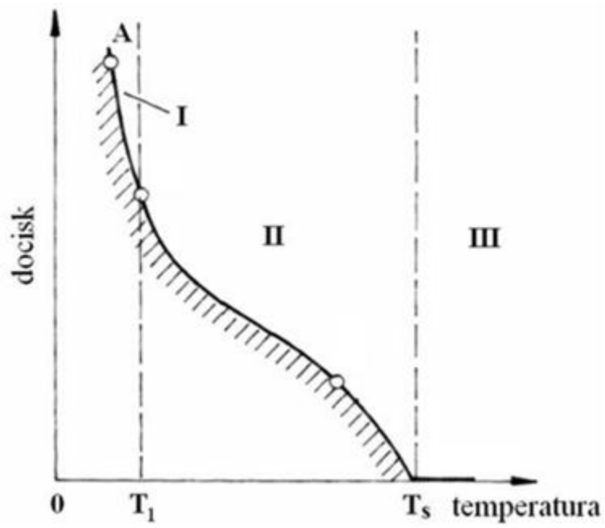

Fig. 13 *Graph of the dependence of temperature and pressure force to obtain a bonded joint [26]*

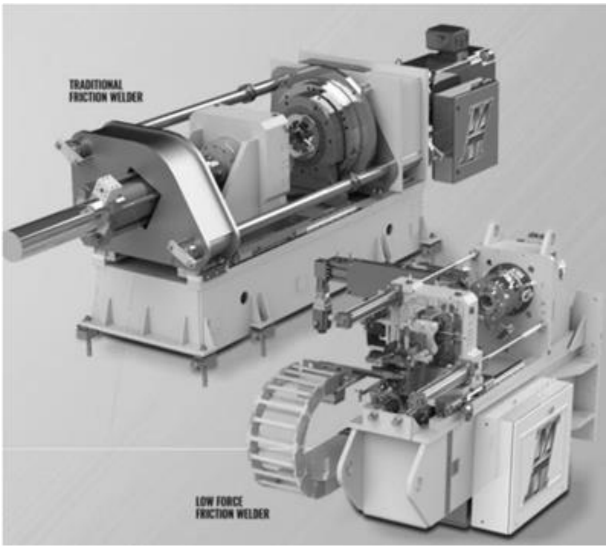

Fig. 14 *MTI Rotary Friction Welder and Low Pressure Welder [28]*

In the production of pistons for internal combustion engines, there are two types of friction welding, and these are:

- Friction butt welding,
- Low pressure friction welding.

Friction butt welding is the most widespread and most used method in friction welding. In this method, two varieties are used, i.e. [27]:

- Continuous drive friction welding,
- Inertial friction welding.

Friction welding with a low pressure force, in order to perform the correct welding, uses the energy coming from the friction process between the elements to be welded and from the induction coil preheating the elements to be joined. The ratio of these two types of energy, depending on the parameters selected, is 9: 1. The induction coil heats the connected elements to a given temperature so that they are pressed against each other and turned by a certain angle. Pre-heating of the joined elements allows for a significant reduction of the forces needed for the proper execution of the weld in relation to the rotary butt welding process. This technology is successfully used to join details of aluminum, alloy steels, stainless steels, nickel superalloys, copper and titanium. [29].

The low pressure welding process itself consists of the following 5 stages [30]:

- Fastening the upper and lower blank,
- Positioning of blanks and induction coil,
- Heating with an induction coil to a given temperature, semi-finished products,
- Friction welding of semi-finished products,
- Unloading.

The process of clamping blanks in the production of pistons is carried out automatically by loading with a robot. The fastening is done by clamping the blanks in special sleeves fastened by hydraulic cylinders. Clamping sleeves position the blanks in relation to each other and transmit the clamping forces and torque. Positioning is used to determine the actual position of the blank and to set the position in relation to each other. It is required to position the blanks to ensure that the surfaces to be welded are parallel. The positioning process takes place in two steps. In the first step, the two blanks are brought together until contact is made to determine the actual distance between them. In the second step, the upper sleeve unfastens the blank and then fastens it in order to compensate for the non-parallel location of the welded surfaces. After completing the positioning process, the parts are returned to the heating position, in which an induction coil is inserted between the two parts in order to heat the parts to the set temperature. After reaching the set temperature, the blanks are pressed together with the set temperature and then rotated in relation to each other by the set angle. The heating process and the welding process are performed in an inert atmosphere of nitrogen [30].

Figure 15 shows an example of a welding station with low pressure. The body is made of a welded bed with two clamps fixed on it. Upper and lower clamp used in order to assemble blanks of the welded piston. The clamp of the bottom and top piston forgings is held in the sleeves by the movement of hydraulic cylinders. In addition, the top clamp moves up and down to press the heated piston blanks to each other so that the welding process can take place. The bottom clamp, on the other hand, performs a rotational movement in relation to its axis after pressing the blanks together by the top clamp. The welding station with low pressure is equipped with an induction coil. The shape of the coil is designed to optimally heat the surface of the welded halves of the piston. The coil is able to move in two axes, the first is used to slide between the two halves of the piston, and the second to evenly position between them in order to heat them evenly to the set temperature. The top and bottom clamps are heavily water-cooled to prevent overheating of the collets [30].

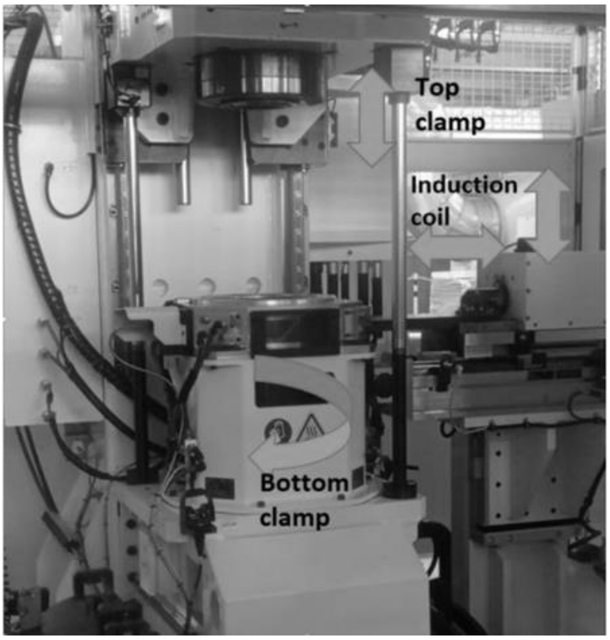

Fig. 15 *Steel piston welding station by MTI [30]*

The appropriate surface quality of the welded parts of the piston, appropriate cleanliness, stability of the heating process and the protective gas atmosphere significantly affect the quality of the connection. Figure 16 shows both parts of the piston before welding. On the left side we can see the forging and on the right side a machined bar which is a semi-finished product of the piston crown. There are two rings: outer and inner. In order for the welding process to be considered as properly performed, the external and internal welds should be properly performed. Due to the hard working conditions of the piston, no connection discontinuities are allowed. The size of the discharge and its shape affect the oil flow in the cooling channel of the piston and thus the service life of the piston. The size and shape of the flash is influenced by the proper friction welding process, and above all, the clamping force, the angle of rotation, the clamping time, and the heating temperature. Figure 17 shows the piston in the welding process in successive stages.

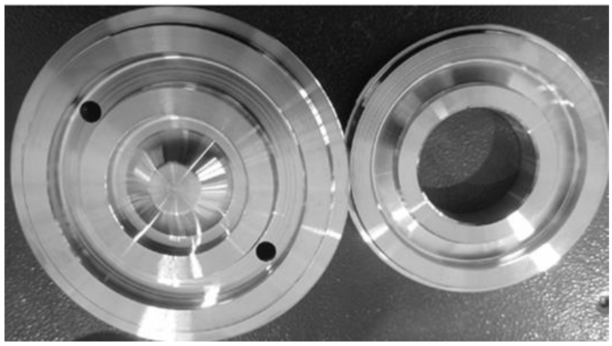

Fig. 16 *Semi-finished products in the production of steel pistons [30]*

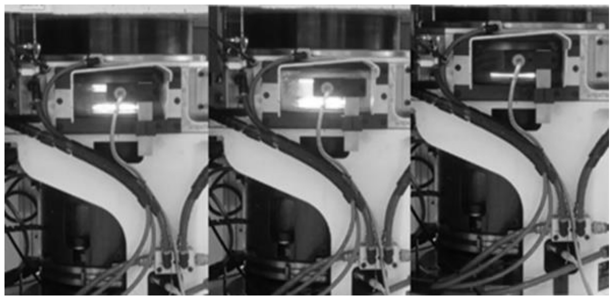

Fig. 17 *View of the subsequent stages of friction welding of the piston with low pressure. [30]*

Friction butt welding is an older method of welding than low pressure friction welding. Many scientific works have been developed describing the phenomena occurring in the welding process and enabling the optimization of welding parameters and the quality of the joint. One of the studies on friction welding and the strength of welds was the work of Messrs. Vill, Kinley, Fomichev and Ratković [31,32,33, 34]. On the optimization of friction welding parameters and the mechanical and metallurgical properties of friction welded bars, it is worth reading the works of Mr. Yilbas [35]. Useful papers describing the optimization of solid-state joining parameters are the papers by Habibizadeh, Budiono, Sejc and Brozek [36, 37, 38, 39]. Another work useful in the production of forged pistons is experimental research on joining joins of medium carbon steel and austenitic stainless steel by the friction welding method of Pan Akata and Sahin [35,40]. On the other hand, the basics of the welding process and the phenomena occurring in this process are the studies of Mr. Myśliwiec and Ambroziak [3].

The main parameters in friction butt welding are: clamping pressure, friction time of the heating phase, upsetting pressure, upsetting time of the forging phase as well as rotational speed. Appropriate selection of these parameters and maintaining cleanliness at the contact point of the welded surfaces guarantees good quality of the welded joint [41]. In this welding method, one blank is fixed permanently and the other is rotated to a given rotational speed to then press it against the stationary blank, as shown in Figures 18a and 18b. On the contact surface, a frictional force generates heat, which together with the pressure force causes swelling of the welded blanks, as shown in Figure 18c. The last step is to stop the rotation of the blank and press them together to obtain the bonding of the blanks as shown in Figure 18d [42].

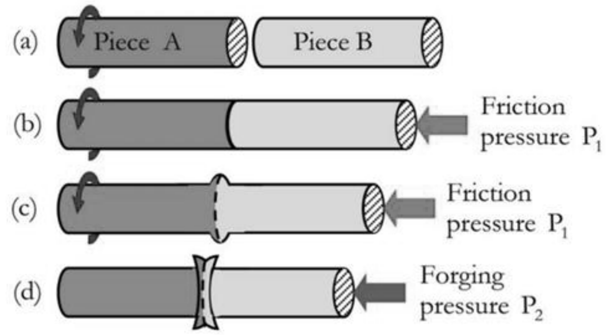

Fig. 18 *Stages of rotary friction butt welding [38]*

There are two variants of rotary friction welding, namely: continuous drive friction welding (also called direct drive friction welding) and inertial friction welding. The most important difference between these friction welding methods is the way the energy is delivered. In direct welding, one half of the element to be welded is attached to a drive motor that maintains a constant rotational speed during the welding process. The process continues until the material is shortened or the braking force is applied. The friction force can be constant throughout the process or vary in stages. The upset stage follows the friction stage and the braking stage. In the friction stage, the necessary heat is generated and the material is swollen, while in the upsetting stage, the weld consolidates. Figure 19 shows the parameters of the welding process with the designated stages.

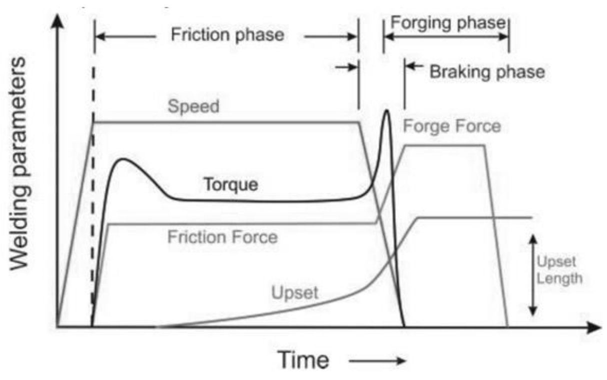

Fig. 19 *The course of parameters of the friction butt welding process [43]*

As a result of the friction process and the heat generated, the weld microstructure differs from the native material. The occurrence of dynamic recrystallization, mutual shear of the newly formed grains causes the formation of a homogeneous structure of a strongly damaged microstructure [40]. The increase in rotational speed causes a microstructure change where the grain boundary becomes thinner with the coarse microstructure of the TMAZ. Too low rotational speed may not be enough to generate enough heat and thus make a proper weld. Initiation of the fatigue strength of welded joints usually begins at the interface, acting as a stress-increasing medium towards TMAZ [45].

The appearance of the weld made by the friction butt welding method is characterized by specific material flashes formed at the stage of upsetting the material. Figure 20 shows the flash formed in the friction welding process. The size and shape of the flash is one of the measures characterizing the quality of the connection, as it indicates the correct course of the process.

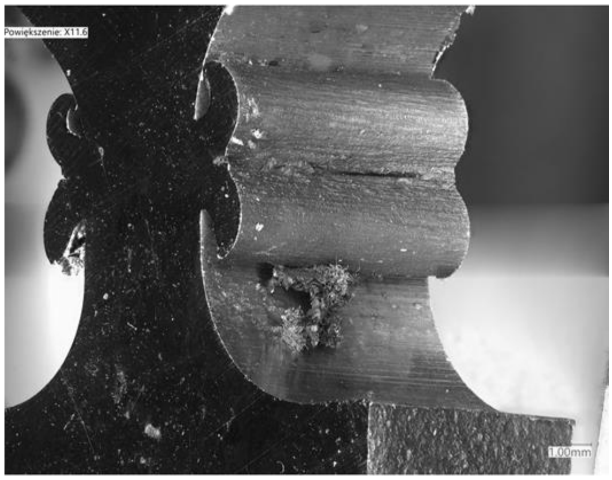

Fig. 20 *The appearance of the weld formed in the process of friction butt welding*

Visual examination of the welded forged piston connection allows for a preliminary analysis of the quality of the welded joints. The shape and size of the flash are assessed as well as the presence of any discontinuities. Figure 21a shows a low-pressure friction-welded piston and figure 21b shows a forged, rotary-butt-welded piston. The low-pressure friction welding of the piston is smooth, with no visible burrs and discontinuities. After welding, the piston crown should be coaxial to the piston skirt. The weld itself takes the shape of a barrel. On the other hand, the weld made by friction butt welding has characteristic flashes. The height of the piston and the oil flow in the cooling channel depend on their shape and size. The weld should be symmetrical and the piston crown coaxial to the skirt. Cracks and discontinuities are unacceptable. The correct weld takes the shape of a curled mustache.

Fig. 21 *Forged steel piston welded: a) by the friction method with low pressure force, b) by the rotary butt welding method*

Destructive analysis of the weld makes it possible to examine the plastic deformation within the joint and to check whether there are any defects in the joint. In industrial applications, 100% of the piston production is tested for weld defects using ultrasound. However, destructive tests are performed when production is launched and every period specified in the standards. Destructive tests include, but are not limited to, macroscopic examination. This test allows to determine the geometric shape of the cross-section of the piston joint, the size and shape of the joint heat-affected zones, macroscopic defects of the material and the weld surface, as well as inhomogeneities in the chemical composition or caused by heat treatment. Figure 22a shows the weld of a steel piston made by friction butt welding, and Figure 22b shows the weld of a steel piston made by friction welding with low pressure. In the production of steel pistons, the lower part of the piston is a blank and the upper part is a rod. Both welds are free from macroscopic defects with pronounced heat affected zones. The shape of the outflow of the material plasticization phase is a clear difference. In the case of friction butt welding, when the material becomes plasticized under the influence of pressure and temperature, the material from the front surface of the semi-finished products is pushed outwards along with surface contamination, creating flashes characteristic for this method. In the case of friction welding with low pressure, Figure 22b, the shape of the flash is completely different. There is no pushing of the material from the face with impurities, only upset. Therefore, in this method of joining materials in a solid state, it is very important to maintain appropriate cleanliness of the surfaces to be welded and to perform the process in the protection of inert gases, which significantly affects the quality of the connection.

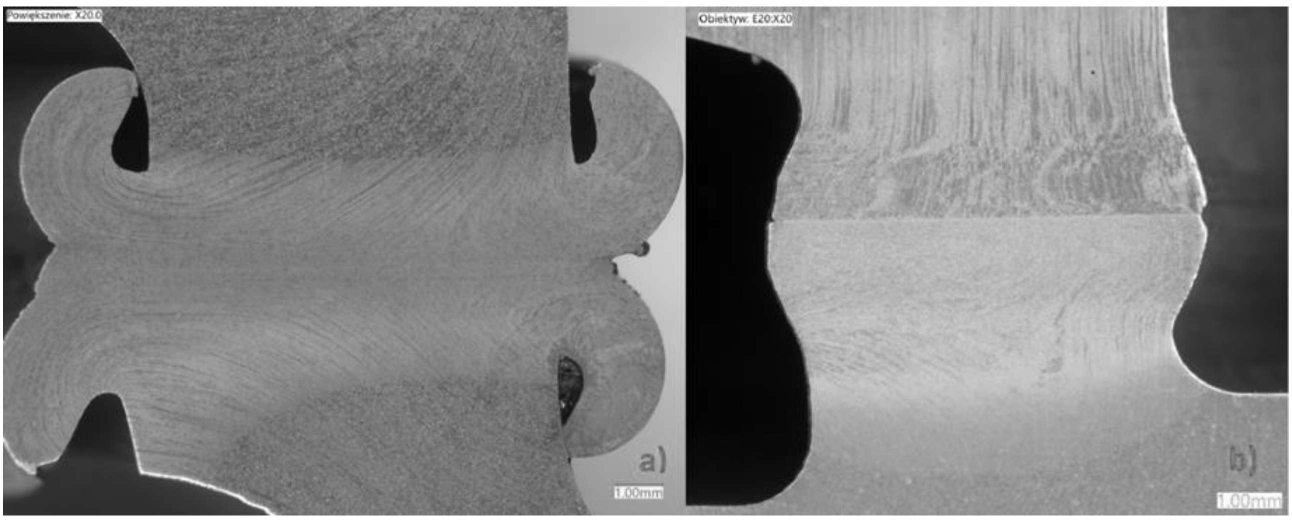

Fig. 22 *The weld is made a) by friction butt welding, b) by friction welding with low pressure*

Regardless of the method of execution, the piston weld seam can be divided into several zones, as shown in Figure 23. The central weld zone is marked as WCZ, the thermomechanical influence zone as TMAZ and the heat impact zone as HAZ. Two of these zones, ie TMAZ and WCZ, belong to the zone of thermomechanical impact. Appropriate selection of parameters ensures similar or better strength properties than the native material [7]. In friction welding with low pressure, the thermomechanical impact zone is much larger than in the case of a joint using rotary butt welding. This is due to the greater and longer temperature impact by heating the blanks with an induction coil. On the other hand, in the case of butt welding, the thermomechanical impact zone is smaller, while the outflow is much larger, which is the result of much greater pressures and a shorter time of exposure to high temperature. It can be concluded that butt welding works well in the production of large steel pistons in which it is important to limit the heat-affected zone, thus increasing the strength of the connection, and in the case of small steel pistons, friction welding with a low pressure force is recommended because little or no flash increases the oil flow in the piston's cooling channel and the loads affecting the small piston are reduced.

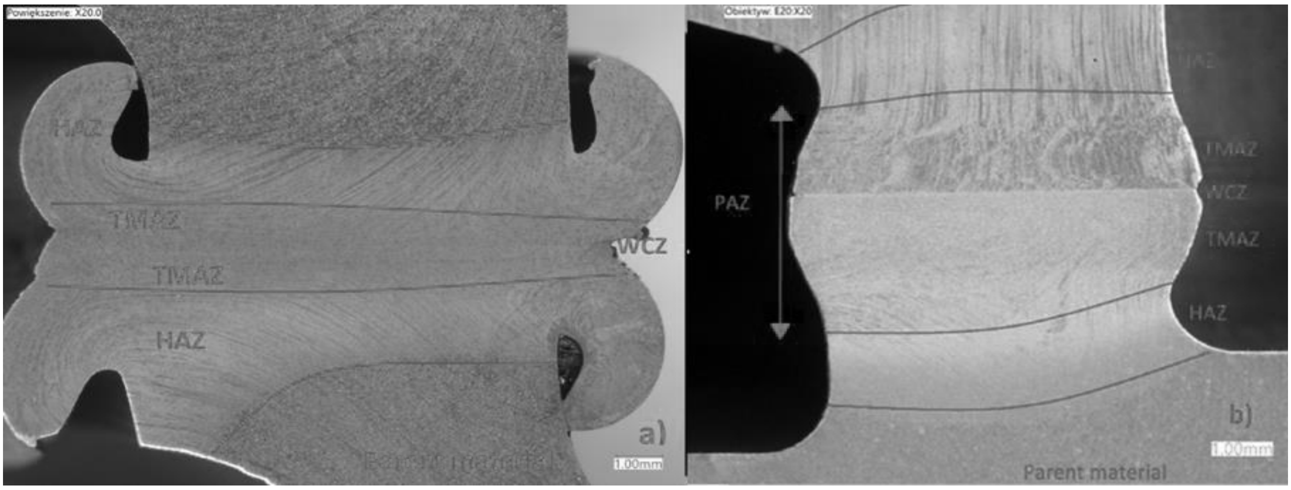

Fig. 23 *Heat affected zones a) friction butt welding, b) low pressure friction welding*

Recalling the first pages of the article describing the effect of heat within the combustion chamber on the durability and functionality of the pistons, the significant influence of the cooling channels under the piston crown should be emphasized. Figure 24a shows the cooling channel of a small steel piston made by friction welding with a low contact force, and Figure 24b shows a large steel piston made by friction butt welding. In large steel pistons, the cooling channel is almost three times larger than that of small steel pistons, therefore the influence of the flash generated in the process of friction butt welding is negligible. The oil flowing through the cooling channel absorbs heat from the piston crown and the ring part. In this case, the cooling channel has dimensions of 31x22 mm, and the outflow from the welding process is 3x7mm, with the outlets not located at one height. In the case of low pressure friction welding, shown in Figure 24a, the cooling channel is 9x11 mm and the flash is 0.6 mm. The outflow in the shape of a small bulge affects the oil flow in the cooling channel to a very small extent, despite a much smaller cooling channel.

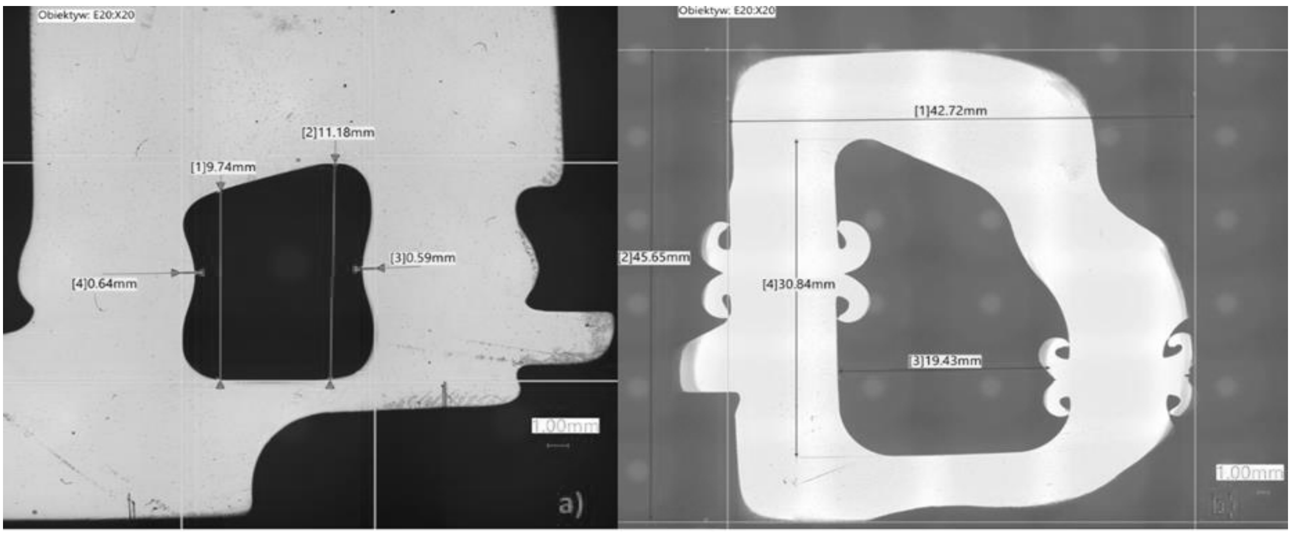

Fig. 24 *Cross-section of the piston's cooling channel, made a) by friction welding with low pressure, b) by friction butt welding*

One of the important measurements proving the quality of the connection is the Vickers method of measuring the hardness of the weld in various zones. Measurement of hardness in the production of steel pistons is performed on the outer and inner rings, additionally, the measurement is performed in the axis of the bolt hole and on the plane perpendicular to the bolt hole. The measurement distance between the points is 0.5 mm made in a zigzag pattern. One of the assumptions of a correctly performed measurement is the presence of at least 5 measurement points in each of the weld zones. Figure 25 shows the positions of the measurement points on the weld.

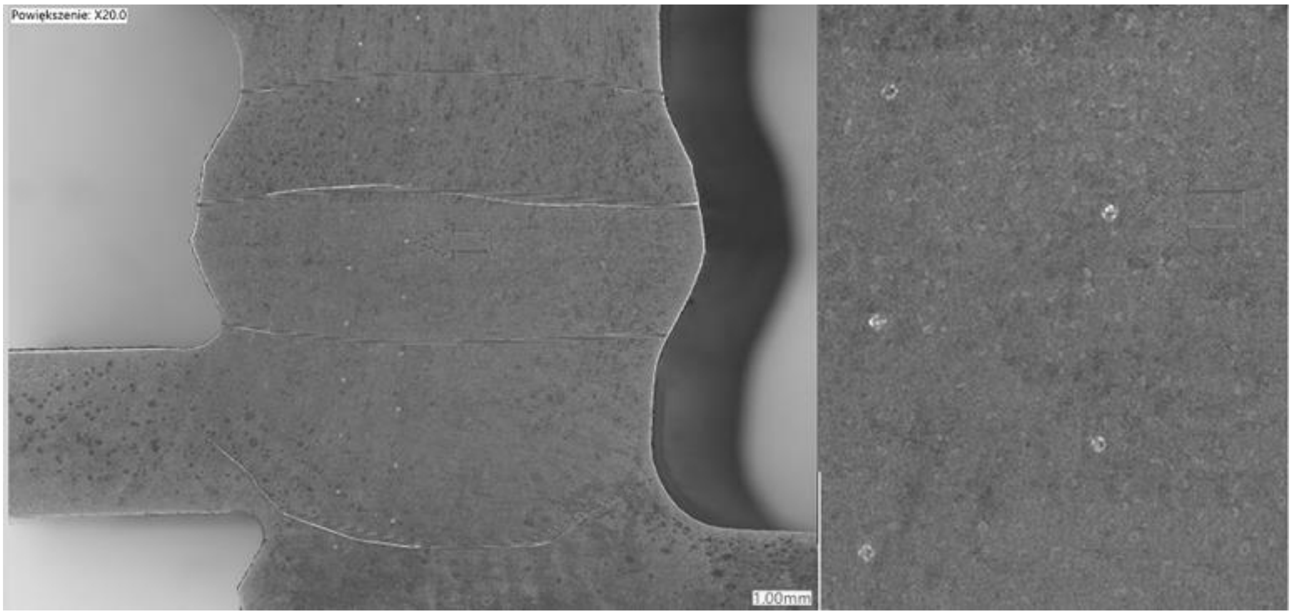

Fig. 25 *Hardness test point positions in the steel piston*

The hardness measurement was made on the weld without heat treatment and the material from which the piston was made was 25HM steel. Lack of heat treatment causes that the hardness measurement results are high, but the shape itself is similar. The hardness measurement results are represented by blue points and the combination of these points forms the hardness curve. The vertical lines in the diagram show the boundaries of the weld zones. The red parabolic curve shows the polynomial hardness trend curve. The weld hardness curve for the outer ring is shown in Figure 26. The graph shows a sharp jump in hardness from 300 HV in the native material to less than 600 HV in the HAZ zone. The hardness in the TMAZ and WCZ zones remain at a similar level with small local jumps. The HAZ is about 2 mm wide on both sides, while the TMAZ is larger and 6 mm wide. The hardness in the TMAZ varies from 510 HV to a maximum of 600 HV.

Figure 27 shows the hardness curve of the inner ring weld made by the low pressure plate welding method using the 150HIW Hybrid Induction welding machine. The chart shows that the heat affected zone is about 12 mm wide. In the HAZ zone, we see a sudden jump in hardness from 300HV in the native material to 500 HV. In the TMAZ zone, the hardness ranges from 510 HV to a maximum of 600 HV. The total width of the TMAZ is 6 mm. The zones are symmetrical to the central high frequency zone.

Figure 28 shows the piston butt friction welding curve. This piston is made of 4140H steel, i.e. 38MnSiVS5. The discussed piston has been tempered after welding in order to reduce the stresses. The tested hardness was performed on the weld in the plane of the axis of the bolt hole. The native material has a hardness of about 280 HV, and the maximum hardness in WCZ is 378 HV. Note the shape of the curve, it is more pointed in the shape of a triangle, while the hardness curve of the piston spline from the friction welding process with low pressure has a trapezoidal shape. Attention is also drawn to the fact that in the process of butt welding, the heat-affected zone is much smaller than in the case of friction welding with a low pressure force.

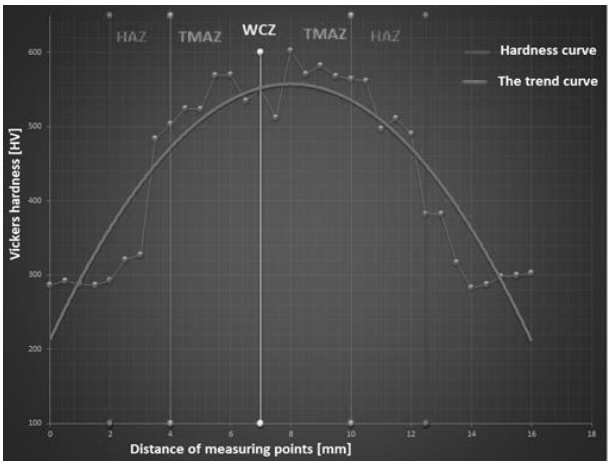

Fig. 26 *Steel piston outer ring hardness curve diagram [30]*

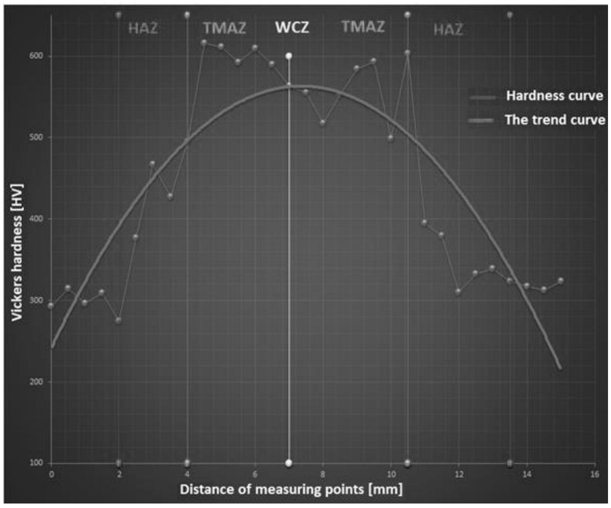

Fig. 27 *Shows the hardness curve of a friction-butt-welded steel piston [30]*

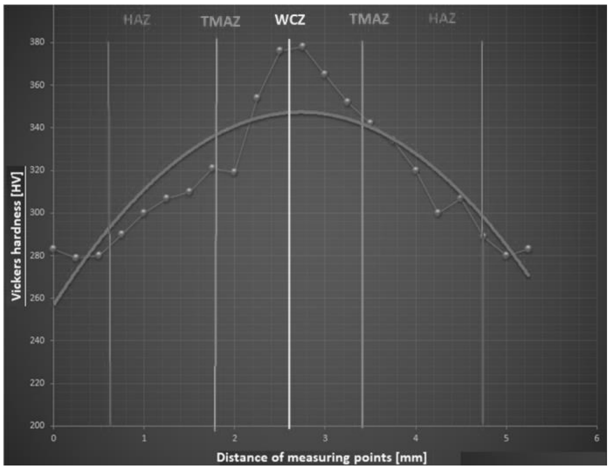

Fig. 28 *Shows the piston butt friction welding curve*

5 Conclusions

Increasingly greater requirements regarding the quality of exhaust gases, competition for the highest possible reliability of combustion vehicles and their economy in everyday use. The requirements for the quality of exhaust gases are dictated by national requirements in the field of environmental protection. On the other hand, failure-free operation and operating economy affect the size of potential customers. Car manufacturers, in order to meet all market requirements, outdo each other in new design solutions, hoping to gain a market advantage. One of the market trends in the automotive industry aimed at increasing reliability and saving cars while maintaining all emission standards are forged steel pistons. In recent years, it has been gaining great recognition among producers.

Steel pistons enable the use of much higher pressures than in aluminum pistons, even over 200 bar, and a significant temperature of up to 400 ° C. In addition, steel pistons offer the possibility of increasing power with the same displacement as their aluminum counterparts, allowing the size of the engines to be reduced. One of the very important advantages of forged steel pistons is their lower thermal expansion than aluminum pistons. As it was presented in the article, the lower thermal expansion allows the use of the piston dimensions closer to the optimal, even in a cold state, with the necessary clearance between the piston and the cylinder. This clearance is much smaller than in the case of aluminum pistons, reducing the frictional forces and deflection of the piston in cold work, increasing its strength. Less clearance also means lower engine oil consumption and lower blow-by emissions. The greater strength and temperature resistance of steel in relation to aluminum alloys allows the use of thinner walls. The thinner walls and lower height of the steel pistons compensate for the higher density of the steel, making the weight of a steel piston similar to that of aluminum pistons. Steel piston internal combustion engines can be smaller, more efficient and lighter.

In industrial application in the production of steel pistons, two methods of friction welding dominate, and they are: friction butt welding and friction welding with low pressure. Friction butt welding dominates the production of large steel pistons. It is a solid-state joining process that has been known for many years. Relatively high pressures make it impossible to weld thin-walled products. On the other hand, the use of high pressures allows for the reduction of the required temperature needed for the welding process. Shorter heating time of the piston formed in the process reduces the heat affected zone. The large, characteristic outflow created in the butt welding process does not adversely affect the oil flow in the piston's cooling channel, because in large steel pistons the cooling channels have much larger cross-sections. The large cross-section of the cooling channel eliminates the influence of outflows, ensuring sufficiently good heat removal from the bottom and ring surfaces of the piston. The case with small steel pistons is a bit more complicated, thinner walls, small cross-section of the cooling channel makes it impossible to use friction butt welding. Therefore, friction welding with a low contact force is most often used. A small, spherical flash on the weld does not adversely affect the oil flow in the cooling channel without reducing the potential for heat transfer from the bottom and the annular part of the piston by the oil flowing through the cooling channel. The low pressure force needed for the welding process to occur allows the use of smaller wall widths than in large pistons. The disadvantage is the necessity to take care of the high quality of the welded surfaces, the necessity to use shielding gases and a large number of process parameters. Although a large number of process parameters also give great opportunities to influence the size of the heat-affected zone of the weld, process time, additional heat treatment of the welded piston can be applied. Determining the optimal parameters of the friction welding process with low pressure force can be determined by the method of experiment or using artificial intelligence based on knowledge from previous runs, the tested physical relationships between process parameters, and readings from process sensors measured in real time. However, due to the extensive topic of determining and optimizing these parameters, another article will be devoted to this issue.

References

[1] WALCZUK, M. BIENIAŚ, J. STRADOMSK, B. JANKOWSKI, A. (2011). Wear of engine pistons – microstructural characteristics of materials used to produce them, Innovatio Press. *Wydawnictwo Naukowe Wyższej Szkoły Ekonomii i Innowacji*. V1. No 1. ISSN: 2084-8005

[2] WRÓBLEWSKI, E. (2019). The Influence of Microgeometry of the Piston Lateral Surface on the Mechanical Efficiency of a Combustion Engine, *Praca Doktorska Politechniki Poznańskiej*. DrOIN 2073

[3] Niewczas, A.(2011). Trwałość zespołu tłok-pierścień tłokowe-cylinder silnika spalinowego. *Wydawnictwo Naukowo Techniczne*, Warszawa. ISBN: 978-83-2042-267-2

[4] WAJAND, J.A. WAJAND, J.T.(2005) Tłokowe silniki spalinowe średnio- i szybkoobrotowe. *Wydawnictwo Naukowo Techniczne*, Warszawa. ISBN: 83-204-3054-2

[5] Products 2021 pistion and component, *MS Motorservice Internation GmbH*, Germany, 2021

[6] ISKRA,A.(2001). The influence of oil and coolant temperature on friction losses of the internal combustion engine, *Wydawnictwo Politechniki Poznańskiej*, Poznań

[7] ISKRA,A.(1996).Stadium konstrukcji I funkcjonowania pierścieni w grupie tłokowo-cylindrowej, *Wydawnictwo* Politechniki *Poznańskiej*, Poznań

[8] Piston Manual, Cylinder and Cylinder Blocks, *Mahle GmbH*, Stuttgart 2012

[9] NING, L. MENG, X. XIE, Y.(2013) Incorporation of deformation in a lubrication analysis for automotive piston skirt-liner system, Proceedings of the Institution of Mechanical Engineers, *Journal of Engineering Tribology*. November 30. ISSN: 1350-6501

[10] WERKMANN, M. BITTER, A. KUZEL, R.(07- 08/2011). Effect of the skirt stiffness on piston related noise, *MTZ*, ISSN 2192-9114

[11] BLUMM, M. BABERG, A. DORNENBURG, F. LEITZMANN, D.(02/2016). Innovative Schaftbeschichtungen für Otto- und Dieselmotorkolben, *MTZ*, ISSN 2192-9114

[12] LITTLEFAIR, B. CRUZ, M. MILLS, R. THEODOSSIADES, S. RAHNEJAT, H. DWYER-JOYVE, R. HOWELL-SMITH, (2013) S. Lubrication of a flexible piston skirt conjunction subjected to thermo-elastic deformation: A combined numerical and experimental investigation," Proceedings of the Institution of Mechanical Engineers, *Journal of Engineering Tribology*, Vol 228(1) 69–81

[13] BABERG,A. FREIDHAGER,M. MERGLER, H. SCHMIDT, K. (12/2012). Aspekte der kolbenmaterialwahl bei Dieselmotoren, *MTZ*, ISSN 2192-9114

[14] DEUSS, T. EHNISH, H. FREIER, R. KUNZEL, R. (12/2013). Friction power measurements of a fired diesel engine - influence of skirt geometry, *MTZ*. ISSN 2192-9114

[15] SCHREER, K. INGO ROTH, I. SCHNEIDER, S. HOLGER EHNIS, H. (10.2014). Analysis of Aluminum and Steel Pistons— Comparison of Friction, Piston Temperature, and Combustion, *Journal of Engineering for Gas Turbines and Power*, Vol. 136

[16] HRDINA, D.(04.2018). Nodular cast iron pistons for Medium Duty applications, *Conference Paper*

[17] WRÓBLEWSKI, E. ISKRA, A. BABIAK, M. (06.2017). Minimizing wear of components piston-cylinder group, Eksploatacja I testy. V6. No 6. ISSN 1509-5878

[18] SCHOMMERS, J. LAGEMANN, V. BOHM, J. BINDER, S. (06.2015). Stahlkolben für Pkw-Dieselmotoren von MercedesBenz Leicht, effizient und zukunftsfähig, *MTZ*, ISSN 2192-9114

[19] BABERG, A. FREIDHAGER, M. MERGLER, H. SCHMIDT, K. (12.2012). Aspekte der kolbenmaterialwahl bei Dieselmotoren, *MTZ*. ISSN 2192-9114

[20] BABERG, A. FREIDHAGER, M. MERGLER, H. SCHMIDT, K.(12.2012). Aspekte der kolbenmaterialwahl bei Dieselmotoren, *MTZ*. ISSN 2192-9114

[21] DHAMAK, C. S. PATIL, B. D. CHAVAN, N. T. DHARMASHALE, V. R. Piston Analysis of IC Engine, *Maharashtra Institute of Technology, Pune, Maharashtra, Indi*. Vol-1 Issue-2 2015. ISSN(O)-2395-4396

[22] LITTLEFAIR, B. DE LA CRUZ, M. THEODOSSIADES, S. MILLS, R. HOWELL-SMITH, S. RAHNEJAT, H. DWYER-JOYCE, R. S. (01.2014). Transient Tribo-Dynamics of Thermo-Elastic Compliant High-Performance Piston Skirts, *Tribology Letters*, ISSN: 1573-2711

[23] KIM, D. ITO, A. ISHIKAWA, Y. OSAWA, K. IWASAKI, Y. (06.2012) Friction Characteristics of Steel Pistons for Diesel Engines, *Journal of Materials Research and Technology*, ISSN 2238-7854

[24] ADILL, H. GERGURI, S. DURODOLA, J. BONATESTA, F. AUDEBERT, F. (03.2019). Comparative Study and Evaluation of Two Different Finite Element Models for Pistion Design, *Journal of Engineering Research and Application*, ISSN 2248-9622

[25] AMBROZIAK, A. (2011). Zgrzewanie tarciowe materiałów o różnych właściwościach, *Oficyna Wydawnicza Politechniki Wrocławskiej*, Wrocław, ISBN 978-83-7493-593-7

[26] MYŚLIWIEC, M. (1972). Cieplno-mechaniczne podstawy spawalnictwa, *WNT*, Warszawa

[27] SAHIN, M.(2010). Łączenie materiałów aluminiowych i miedzianych za pomocą zgrzewania tarciowego. wewn. J. Przysł. *Producent Technol.*,Tom. 49, s. 527-534

[28] ttps://blog-mtiwelding-com.translate.goog/lowforce-frictionwelding?_x_tr_sl=en&_x_tr_tl=pl&_x _tr_hl=pl&_x _tr_pto=nui,sc. dostęp 05.03.2022

[29] JERRY GPULD, E. EWI Adams, D. (2020). Low Force Friction Welds in 4130 Steel, A Preliminary Microstructural Characterization, *Manufacturing Technology*, Inc.

[30] ŻURAWSKI, P. (02.2022). Analysis of low force friction welding process in the industrial environment, *International Journal of Engineering and Innovative Technology*, ISSN: 2277-3754

[31] VI, V. (1962). Friction welding of metals, *AWS New York Welding Society*, (OCoLC)568076616

[32] KINLEY, W.(1962). Inertia welding simple in principle and application, *weld metals* Fab, Oct., pp 585–589

[33] FUKUMOTO, S. TSUBAKINO, H. OKITA, K. ARITOSHI, M. TOMITA, T.(1999). Friction welding process of 5052 aluminum alloy to 304 stainless steel, *Mater Sci Techno*

[34] RATKOVIĆ, N. LAZIĆ, V. ARSIĆ, D. NIKOLIĆ, R.R. MESKO, J. NIGROVIC, R. (2016) . Influence of the Friction Time on the Shape and Microstructure of the Mixing Zone of the Friction Welded Joint, *Manufacturing Technology,* ISSN 1213–2489

[35] YLBAS, B.S. (1995). Friction welding of St-Al and Al-Cu materials, *Journal of Materials Processing Technology*, Vol. 49, Nº. 3-4

[36] HABIBIZADEH, A. HONARPISHEH, M. GOLABI, S. (2021), Determining Optimum Shear Strength of Friction Stir Spot Welding Parameters of AA1050/C10100 Joints, *Manufacturing Technology,* ISSN 1213–2489

[37] BUDIONO, Y. MARTOWIBOWO, S. Y. (2017), Optimization of Resistance Spot Welding Process using Response Surface Methodology and Simulated Annealing, *Manufacturing Technology,* ISSN 1213–2489

[38] SEJC, P. BELANOVA, J. GABRISOVA, Z. VANKO, B. (2020), The Influence of Parameters of the Resistance Projection Welding of M10 Steel Nuts to the Galvanized Steel Sheet DP 600 on Selected Joint Characteristics, *Manufacturing Technology,* ISSN 1213–2489

[39] BROZEK, M. (2014), Working Variables Optimization of Resistance Spot Welding, *Manufacturing Technology,* ISSN 1213–2489.

[40] SAHIN.M , AKATA,HE.(2003). Joining with friction welding of plastically deformed steel, J *Mater Process Technol.* ISSN: 0924-0136

[41] SAHIN, M. AKATA, HE.(2004). An experimental study on friction welding of medium carbon and austenitic stainless-steel components, *Indust Lubricat Tribol*

[42] SHUBHAVARDHAN, RN. SURENDRAN, S. Friction Welding to Join Dissimilar Metals, *International Journal of Emerging Technology and* Advanced *Engineering*, ISSN 2250–2459

[43] F. Khalfallah, Z. Boumerzoug, S. Rajakumar and E. Raouache, Optimization by RSM on rotary friction welding of AA1100 aluminum alloy and mild steel, *International Review of Applied Sciences and Engineering* 11.2020. ISSN 2063-4269

[44] RAMESH, A.P. SUBRAMANIYAN, M. ESWARAN, P. (2019) EVIEW ON

FRICTION WELDING OF SIMILAR/ DISSIMILAR METALS, *Journal of Physics: Conference* Series *1362*

ISSN: 1742-6596

[45] SKOWROŃSKA, B. CHMIELOWSKI, T. PACHLA, W. KULCZYK, M. SKIBA, J. PRESZ, W. (2019) Friction Weldability of UFG 316L Stainless Steel, *Arch. Metall. Mater*. 64 ISSN 1733-3490

[46] S ASMITO, A. ILMAN, M. N. ISWANTO, P. T. and MUSLIH, R. (2022) Effect of Rotational Speed on Static and Fatigue Properties of Rotary Friction Welded Dissimilar Aluminium Alloy Joints, *metals*, ISSN: 2075-4701

[47] MCANDREW A. R. , COLEGROVE, P. A. BUHR, C. FLIPO, B. VAIRIS, A. (2019) A literature review of Ti-6Al-4V linear friction welding

[48] SHETE, N . DEOKAR, S. U. (04.2019) A Review Paper on Rotary Friction Welding, *International Conference on Ideas, Impact and Innovation in Mechanical Engineering*, ISSN: 2321-8169