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AHSS—Construction Material Used in Smart Cities

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Abstract: With the level of development of the smart city, there are more and more research sub-areas in which the latest material and technological solutions are used, enabling the proper management and functioning of these cities. On the one hand, the introduced materials and technologies are designed to facilitate the functioning of residents both in the urban space and at home; on the other hand, the implemented solutions strive to be consistent with the principles of sustainable development. As shown in this article, reports on new technical and technological solutions and their positive and negative effects are strongly emphasized in publications on the development of smart cities. The most highlighted materials research in the smart city area concerns smart materials and their characteristics and applications. A research gap in this area is in the presentation of material solutions, particularly materials intended for the load-bearing structures of vehicles (electric vehicles, flying vehicles) or infrastructure elements (buildings, shelters, etc.) designed to increase the durability of the structure while reducing its weight. This paper aims to comprehensively present the most important research areas related to the functioning of smart cities in light of previous research, with particular emphasis on new material solutions used for thin-walled load-bearing structures in smart cities made of AHSS (advanced high-strength steel). These solutions are very essential for smart cities because their use allows for the installation of additional devices, sensors, transmitters, antennas, etc., without increasing the total weight of the structure; they reduce the number of raw materials used for production (lighter and durable thin structures), ensure lower energy consumption (e.g., lighter vehicles), and also increase the passive safety of systems or increase their lifting capacity (e.g., the possibility of transporting more people using transports at the same time; the possibility of designing and arranging, e.g., green gardens on buildings; etc.). AHSS-welded joints are usually characterized by too-low strength in the base material or a tendency to crack. Thus, the research problem is producing a light and durable AHSS structure using welding processes. The research presented in this article concerns the possibility of producing welded joints using the Metal Active Gas (MAG) process. The test methods include the assessment of the quality of joints, such as through visual examination (VT); according to the requirements of PN-EN ISO 17638; magnetic particle testing (MT); according to PN-EN ISO 17638; and the assessment of the selected mechanical properties, such as tensile strength tests, bending tests, and fatigue strength checks. These methods enable the selection of the correct joints, without welding defects. The results have a practical implication; advanced production technology for obtaining AHSS joints can be used in the construction of the load-bearing elements of mobile vehicles or parts of point infrastructure (shelters, bus stops). The obtained joint is characterized by adequate strength for the production of the assumed structures. The originality of the manuscript is the presentation of a new, cheaper, and uncomplicated solution for obtaining an AHSS joint with good mechanical properties. The application of the presented solution also contributes to sustainable development (lower fuel and material consumption use by mobile vehicles) and may contribute to increasing the load capacity of mobile vehicles (the possibility of transporting more people).

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1. Introduction—Smart City Research Areas

One of the distinguishing features of the development of civilization is the level of urban development. In the twenty-first century, the quality of urban areas is identified by their ability to meet the needs of life at a high level for both current and future residents. According to the United Nations, it is estimated that by 2030, 66% of the world's population will live in urban areas. New cities will be created, and old ones will be modernized [1,2]. Cities are becoming increasingly problematic for the following reasons:

- Too much urbanization in areas (a lack of so-called "green places") (residential buildings, industrial areas, infrastructure related to transportation such as charging stations, fuels, roadways, and large areas intended for parking and garage spaces);
- Waste management (including hazardous waste) and consumables (e.g., fuels, lubricating oils, engine or air conditioning coolants, windscreen washer fluids, etc.);
- The emission of substances harmful to the environment;
- Noise and vibrations;
- Excessive traffic from motor vehicles;
- Shrinking resources.

Cities are the central element of economic, social, and cultural life. They are the dominant spatial form.

This complex organism consists of many interrelated systems, both social and technical. These systems determine the quality, including comfort and the standard of living, of the city [3]. The development of civilization significantly affects environmental degradation, including the quality of our lives.

Pollution factors include the following:

- Air, e.g., harmful emitted substances contained in the exhaust gases of traction motors and the gases and vapors of liquids from technological processes or those used in the handling and management of used vehicles;
- Soil, e.g., through leaks from consumables, heavy metal compounds constituting the components of exhaust gases, and dust;
- Water, e.g., liquid leaks; the emission of substances harmful to the environment, e.g., from automotive sources; and the violation of water regulations, e.g., significant construction investments are acutely felt by a person, affecting his mental and physical comfort. Along with the development of urban planning, the number of cases of cancer, food contact or inhalation allergies, and asthma is increasing.

City governments around the world are limiting the number of motor vehicles allowed to move around cities, developing public transportation, giving up traditional fuels, and looking for alternative solutions (electromobility, car sharing, flying vehicles, and others). A modern city should be friendly to the environment and, at the same time, comfortable for residents and entrepreneurs, who should meet their expectations. One of the concepts of urban development is the smart city (S.C.), also known in the literature as the digital city [4], intelligent city [5], or smart grid [6]. The concept is constantly being developed [7]. Most of the literature items from the first decade of the twenty-first century presenting the smart city are limited to determining the impact of information and communication technologies on improving the functioning of cities [8]. This direction of research can still be considered the leading one [9]. It is very essential from the point of view of the concept itself, although this view is limited. The smart city should act as an efficient organism whose individual parts cooperate, ensuring harmonious development, which, in turn, should translate into an increase in the functionality of the city and an improvement in the quality of life of residents. Therefore, according to the authors, the smart city, nowadays, is not only an IT and technological concept [10] but also includes all activities aimed at improving the functionality of the system, which is the city.

Undoubtedly, the fourth industrial revolution offers new opportunities for more effective and holistic city management and improves the well-being of residents. Information and communication solutions used in smart cities enable more efficient natural resource management [11], e.g., water, raw materials, and renewable energy.

Environmental factors include the following:

- Engineering, e.g., buildings, transportation, IT communication;
- Humans (including health, e.g., air status alerts);
- The influence of people's purchasing decisions, choices, etc.

Functions that meet the designated and assumed needs of residents and other users (e.g., tourists, employees, commuters, trainees, etc.) are associated with the implementation of tasks in individual areas of the smart city. Table 1 presents the most critical research areas regarding the smart city. These include smart buildings, smart Environments, intelligent energy, smart transportation, and intelligent IT communication.

Table 1. Smart city research areas.

Research Areas for Smart Cities	Examples from the Literature
Smart buildings (ports, airports, offices, etc.): 	• D. Snoonian, 2003 [12]. • K. Alanne, S. Sierla, 2022 [13]. • A.H. Buckman, et al., 2014 [14].
Smart environment: 	• L. Na Lee, M. Jeong Kim, 2019 [15]. • M. Kumar, et al., 2021 [16]. • E. Torunski, et al., 2012 [17].

Table 1. *Cont.*

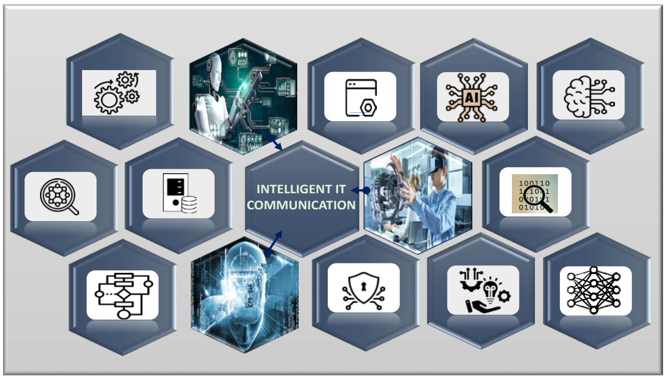
Research Areas for Smart Cities	Examples from the Literature
Smart energy:  	• Zhanyu Ma, et al., 2017 [18]. • Seyed Mehdi Hakimi, Arezoo Hasankhani, 2019 [19].
Intelligent IT communication:  	• M. Dhingra and S. Chattopadhyay, 2022 [20]. • David J. Gunkel, 2012 [21]. • Z. Zhang, 2021 [22].
Intelligent transport:  	• Burlacu, M.; Boboc, R.G.; Butilă, 2022 [23]. • Zantalis, F.; et al., 2019 [24]. • M. Rodrigues, et al., 2017 [25]. • C. Kiran, et al., 2020 [26].

Table 1's first column presents icons representing individual research sub-areas in the smart city concept. The icons symbolize many applications of new mobile devices, technologies, and IT solutions. The research areas represented in the literature related to the smart city are marked with these symbols. However, there is no emphasis on the use of the latest construction materials. No such icon has been identified in any area. Smart city planning must be comprehensive and urgently changed; it cannot be limited only to new solutions in the field of information transfer and data analysis. In order for future structures to be improved and able to cooperate with new technological solutions, it is also necessary to focus on construction materials. The analysis of publications (Table 1) and research areas related to smart cities indicates that the harmonious development of cities must take place simultaneously in each of these areas, and this requires research conducted within many scientific disciplines. According to the authors, only then can the concept of a modern city become smart. Otherwise, you can only talk about smart products and services, not the whole city.

2. Smart City Research Directions

An important direction in the development of research work over the last decade has been to indicate the impact of external factors (globalization, migrations, disasters, wars) and internal factors (local law, wealth, availability of technology, terrain, etc.) on the formation of smart cities. In this respect, the literature on the subject also combines the concept of sustainable development with the smart city concept. Modern cities offer faster, practice-based, and well-established responses to sustainability challenges. Unfortunately, the combination of these two concepts is still dominated by research on the impact of modern information technologies on the environment [27,28]. However, the sustainable development of smart cities can be implemented in many ways, e.g., using new production technologies and materials to reduce the consumption of raw materials, adapting architecture or communication to the needs of each age group, and creating friendly spaces.

In addition, information technology can cause deepening and growing inequalities. The publications [29,30] present the impact of technology development and its possible adverse effects. This broad research direction draws attention, among others, to the following [31–35]:

- Human safety (accidents involving autonomous vehicles, bots, responsibility for decisions);
- Security, including sensitive information;
- The possibility of technological abuse (bad faith, state surveillance, the transmission of inappropriate or biased information, control of human choices);
- Growing inequalities related to the digital exclusion of the poor and the elderly;
- Cyber-attacks leading to blockades of services, plants, transports, and entire cities and other disasters.

In the literature on smart cities, the impact of materials engineering on the formation of modern structures and devices supporting human functioning has also been noted [36,37]. The most advanced and widespread research in this direction concerns the properties, manufacturing, and application of smart materials in smart cities [38]. Smart materials include, e.g., glass that can dynamically change optical properties and materials supporting the spread of sunlight in residential or public buildings [39]. Textiles that change colors and monitor health and human body temperature; weather-sensitive clothing fibers that use nanotechnology or polymers to indicate whether the food stored in them is fresh; and many other solutions have been presented, e.g., in [40].

Smart materials are also used to manage a smart city effectively. Many transmitters and sensors are installed in the city, which must enable the transmission and subsequent analysis of data and real-time responses to events. Increasingly, antennas are designed from new materials—metamaterials. The structural symmetries of these materials allow for the appropriate refraction of waves; as a result, the transmitted signal can avoid obstacles. The solution enables the uninterrupted transmission of digital data at millimeter wavelengths. Examples of smart materials, with references from the literature, are provided in Table 2.

Table 2. Smart materials in smart cities.

Group of Smart Materials	Applications in Smart Cities—Examples	Literature
Piezoelectric	• The piezoelectric property allows opportunities for implementing renewable and sustainable energy through power harvesting and self-sustained smart sensing in buildings. • Piezoelectric materials in smart cities are used in energy harvesters, sensors, and actuators for various building systems or healthcare monitoring (e.g., they can measure, in real-time, the physiological functions of human organisms via dynamic measurements). • Piezoelectric floors are a new technology that could be used in self-powered smart cities of the future, as demonstrated at NASA's Kennedy Space Center's Visitor Complex at Cape Canaveral in 2017.	• Chandra Sekhar, et al., 2021 [41]. • A. Zaszczynska et al., 2020 [42]. • NASA's Kennedy Space Center's Visitor Complex at Cape Canaveral, 2017 [43].
Shape Memory Materials/Shape Memory Effects	• There are known applications for shape memory materials in the smart automotive sector. Smart materials might easily replace traditional elements (motors, hydraulic devices, etc.). • Smart materials could efficiently reduce the weight, size, and complexity of objects. In addition, they are impervious to water, moisture, dust, and other elements that can wreak havoc on electric motors. The materials can be used in many movable features, such as replacing the electric motors traditionally used to activate car seats, windows, and locks.	• A. Spark, 2014 [44].
Chromoactive materials	These materials can be used in the following ways: • Liquid crystals for the fabrication of displays incorporated into technological devices (TVs, calculators, the screens of eBooks, tablets, watches); • Metallomesogens, as multifunctional materials, can combine the fluidic state of the mesophases with properties such as photo- and electroluminescence, which offer new and exciting possibilities for optoelectronics, energy, the environment, and even biomedicine; • Near-infrared (NIR) luminescent materials can be used for food composition analysis, night vision, biosensors, and so on, in smart cities.	• C. Cuerva, et al., 2016 [45]. • C. Cuerva, et al., 2021 [46]. • Y. Wei, et al., 2021 [47]. • S. Ding, et al., 2022 [48].
Magnetorheological materials	MREs can be used in Smart City as vibration absorbers, vibration isolators, sensors, controllable valves, and adaptive beam structures, as well as sensors and actuators; for example, they can be used as: ✓ Force sensors; ✓ Magnetoresistive sensors; ✓ Magneto-sensitive strain sensors; ✓ Flexible tri-axis tactile sensors; ✓ Self-powered tribo-sensors; ✓ Combined magnetic and mechanical sensors; ✓ Soft actuators; ✓ Actuators for valves; ✓ MEMS magnetometers. • Moreover, the microwave responses and 3D printing properties of MREs have also recently been reported. It is worth pointing out that the application of MREs is developing quickly.	• L. Taixiang, Y. Xu. 2019 [49].

Table 2. *Cont.*

<table>
<tr><th>Group of Smart Materials</th><th>Applications in Smart Cities—Examples</th><th>Literature</th></tr>
<tr><td>Smart concrete</td><td>Smart concrete materials are commonly used to improve city operations and management using the following methods:
• Tracking traffic;
• Monitoring crowds at events;
• Improving the performance of utility systems and public transportation.
Self-sensing materials can monitor the following:
• Civil infrastructures;
• The health of structural materials in smart cities (structural health monitoring sensors are innovative transducers combining enhanced durability and distributed measurements, thus providing greater scalability regarding sensing size).
Examples of possible field applications for developed nanocomposite cement-based sensors include
• Traffic monitoring;
• Parking management;
• Condition assessments of masonry;
• Creating concrete structures with self-sensing capabilities.
Self-healing materials are elements that can achieve self-repair and return to their original conditions in a smart city. The self-healing of these materials is achieved by reducing cracks and maintenance expenses and increasing strength and durability. Self-healing materials are used for “bacterial encapsulation, self-healing with self-controlled tight crack width.”
• CNT-based cementitious sensors represent a novelty in the field of structural engineering and SHM. These nanocomposites are suitable for fabricating smart self-sensing sensors, which can be used to improve city operations and management by deploying large arrays.
• Some application examples include the following:
• Weigh-in motion sensing via self-sensing cementitious slabs during assistance;
• Traffic and crowd management by detecting a weight and its location.
• A promising application is the structural health monitoring of the following:
  ✓ Civil infrastructures, including energy systems (e.g., dams, wind turbine bases);
  ✓ Transportation infrastructures (e.g., roads, bridges);
  ✓ Building structures (e.g., historic structures), which would enable swift condition assessment, e.g., post-earthquake.
• Other prospective applications for cement composites doped with electrically conductive nanoparticles within smart cities include the following:
  ✓ Conductive slabs with antistatic abilities for data and computer centers in smart grids;
  ✓ Thermally conductive concrete road pavement for de-icing applications using electrical power;
  ✓ Thermally conductive concrete for geothermal applications;
  ✓ Embedded thermal and hygroscopic sensors for environmental control, including applications within critical environments such as museums and thermally and energetically efficient concrete materials, including a combination of conductive nanoparticles, phase-change materials, and more.</td><td>• A. D’Alessandro, et al., 2015 [50].
• N. Makul, 2020 [51].</td></tr>
</table>

Table 2. *Cont.*

Group of Smart Materials	Applications in Smart Cities—Examples	Literature
Smart bridges	• Smart bridges are instrumental in determining the flow of people (citizens and tourists) inside a smart city. These bridges are equipped with sensors that can measure several indicators, for instance, the number of people crossing the bridge on an hourly basis or how much the bridge moves based on weight. ✓ This increases the safety of the construction; ✓ This allows for structural management and ensures long-term quality.	• R. van der Zwan, 2022 [52]. • D. Inaudi, 2009 [53].
Shapeshifting metals	Potential applications of these materials in smart cities include the following: ✓ Soft robotics; ✓ Intelligent electronics; ✓ Computer graphics; ✓ Flexible displays; ✓ Self-organizing electronics. There are many potential uses for small robots that can move around places too small or convoluted for humans to manage with typical tools, from finicky repair work to targeted drug delivery. Miniature machines can switch from solid to liquid and back again to squeeze into tight spaces and perform tasks such as soldering a circuit board.	• A. Saadeh, 2023 [54] • N. Tanjeem, et al., 2022 [55]
Smart glass	Smart glass is used in vehicles and building in smart cities. Adjustable-tint windows can automatically adapt to ambient light conditions to improve visibility (in buildings or cars) or safety (in vehicles on the road or workplaces). Heat-blocking windows and sunroofs reduce the need for air conditioning and its components in the building, and this can lower fuel consumption and emissions in cars. Smart glass is especially attractive to electric vehicle (EV) makers.	• D. Kim, Y. Choi, 2021 [56]. • A. Corning, 2022 [57].

Innovations in materials engineering regarding the smart city concept also concern the material and technological concept, which covers the development of materials for the load-bearing structures of vehicles and buildings, reinforcement structures, etc. Unfortunately, this topic is treated only briefly in the literature. Knowhow certainly plays a significant role in this respect. Companies protect their inventions. Most often, publications describe ready-made general solutions, e.g., a mobile vehicle (its limitations and advantages); an intelligent building; or an entire housing estate, robots, bots, artificial intelligence, or modern service systems, including new applications. There are almost no scientific or industrial publications in the field of newly developed construction materials combined with the technology of their production and processing regarding the needs of smart cities. However, innovative materials and components determine the properties of future products; innovative manufacturing technologies increase the scope of application for materials and enable the processing and combination of those that, until now, were considered difficult or very complex to a machine. According to the authors, an essential element of every smart city is the material and technological concept, enabling the development and production of new structures with better, desirable properties. The material itself does not necessarily have to be smart. Solutions are sought for the following subjects:

- Slimming down vehicle structures, translating into the following factors: Lower fuel consumption in public transportation (for example, using materials with high tensile strength, good impact strength, and others); Increasing the lifting capacity of existing mobile vehicle structures while also reducing weight (the possibility of transporting more people, reducing the number of raw materials used for production); Developing technologies for mobile flying vehicles, requiring light and reinforced structures (new composite materials, aluminum alloys, AHSS steels, and others).

- Developing materials, e.g., to strengthen the structure of buildings so that parking spaces for flying vehicles or oases of greenery, gardens, and rest areas can be created on their roofs in the future;
- Technologies and materials used in devices for energy acquisition and recovery or transportation (e.g., new connection technologies minimizing energy loss at the point of contact of materials—patents).

Listed above are only some of the material and technological research directions concerning construction materials that can be used in a smart city; these affect reductions in resources and energy consumption, and indirectly, they also affect the comfort of the lives of residents. These solutions are some of the determinants of the sustainable development of modern cities. Research on these materials can be found in articles devoted to materials engineering and mechanics, but for people dealing with smart cities, searching for information in entirely different areas can be tedious and ineffective. Sometimes it is very difficult to find and relate to topics because they are insufficient or not exposed at all to the field of smart cities. This is a significant research gap. However, the material and technological concept is fundamental. The organism that is the city must function efficiently, so every part of it must be adequately designed, manufactured, and operated.

3. Purpose of the Article

As shown in the previous section, the directions of the research related to smart cities treat the development of the material and technological concept too vaguely in terms of construction materials cooperating with smart materials. Although the importance of the sustainable development of a smart city is widely accepted, somehow, the research presented in the literature in this area bypasses the problem of selecting construction materials for safe, durable structures. According to the literature [58,59], even recently completed buildings or manufactured vehicles often do not meet high standards, e.g., in terms of energy saving. Therefore, it is desirable for point infrastructure, including bus and bicycle shelters, to be equipped with solar panels. In addition to important elements such as the construction of solar panels and their positioning (south-facing, in sunny places), a subject in the implementation of projects widely presented in the literature [58] is the important role played by the creation of appropriate, durable, and transparent structures that can fit into particular contexts. The main problem in this regard is the desire to reduce the cross-section of the structure's walls while ensuring its strength. Sheds in a smart city should be multifunctional and friendly to customers and the environment. Therefore, additional elements are mounted on them, such as flowers, panels, transmitters, sensors, and monitors, which constitute an additional load on the structure. A similar problem regarding the production of relatively light and safe supporting structures occurs in vehicles. A lighter structure allows for the lower energy consumption needed to power the vehicle and, in the case of transportation, a lighter but more durable structure allows for the transporting of more people and things. This is why the solution presented in this article, which enables the creation of light and durable structures, is so important for smart cities.

Therefore, this article aims to present research on the possibilities of using new-generation AHSS for reinforced and light welded structures in smart cities, such as for the following:

- Electric vehicles;
- The load-bearing infrastructure of shelters and stops;
- Other buildings.

In the smart city concept, there is a tendency to use construction materials with lower density, greater strength, and better functional properties than previously used materials. Thanks to the use of these materials, it is possible to reduce the weight of the structure, which applies to the following subjects:

Vehicles

- The lower consumption of raw materials for production; the possibility of using profiles with a thickness of less than 2 mm;
- Lower fuel/energy consumption and, thus, reductions in CO_2 consumption;
- Increasing the passive safety of the vehicle (e.g., the use of high-strength steels for battery housings in electric vehicles);
- Increasing the durability of elements, thus extending repair intervals and reducing the environmental burden of waste materials;
- The ability to transport goods (things, people) with an increased load.

Point infrastructure:

- The ease of shaping thin-walled durable structures, giving the impression of lightness, and, at the same time, the structure can be glazed, e.g., ceilings made of smart glass; additional elements can be mounted on the structure, e.g., solar panels, monitors, mini-gardens, so-called green roofs, etc.;
- Increasing the passive safety of the structure; the structures are resistant to changing weather conditions because they are characterized by higher tensile strength than alloy steels and increased durability in the discussed operating conditions concerning aluminum alloys.

Buildings:

- Reduced consumption of raw materials for production, such by using steel pipe trusses with thinner walls, with a thickness of up to 2 mm for a structure not exposed to weather conditions and 3 mm for a structure exposed to weather conditions;
- Increased fatigue life of AHSS structures, which translates into increased structural safety;
- The possibility of replacing elements that are difficult to access for maintenance with more durable elements in places where it is not possible to use self-repair elements.

All the above elements of thin-walled smart city structures must be characterized by sufficiently high operational properties, including a tensile strength of at least 500 MPa and a fatigue strength of at least 350 MPa. The manufactured structure should not adversely cause an increase in the emission of substances harmful to the environment. On the other hand, for economic reasons, the cost of the developed technology, materials used, and consumables used in the manufacturing process should not be too high. The AHSS grades DOCOL 1200 M and DOCOL 1300 M are characterized by appropriate high-strength properties and were selected for this study. The technology of joining these materials using Metal Active Gas (MAG) welding was chosen—a generally available and relatively cheap technology. The places where structures are joined are the so-called weak link because, most often, they are characterized by much lower strength properties than native materials. Therefore, as part of the development and determination of the possibility of using new-generation AHSSs for reinforced and light welded structures in smart cities, we checked whether the selected welding parameters allow for the production of joints with appropriate strength characteristics. The materials and research methodology are presented in the following sections.

4. Research Material

The excellent mechanical properties of AHSSs make these materials suitable for lightweight, thin-walled structures that can be applied to various elements of a smart city's welded structures, replacing non-alloy steels and some aluminum alloys [60].

Steels from the AHSS group are characterized by worse weldability than classic non-alloy steels due to the martensitic structure dominating them. This structure undergoes phase transformations in the heat-affected zone. The phase transformations determine the mechanical properties of the joint. Alloying elements can be introduced to the weld, allowing for an increase in strength and a stand with reasonably good strength [61,62]. In the MAG (Metal Active Gas) process, this is achieved through the use of electrode wires of different chemical compositions and the appropriate selection of welding parameters. Therefore, MAG (Metal Active Gas) connectors were made with various electrode wires and using different gas mixtures. The thickness of the joints was adopted for relatively thin profiles—1.8 mm, which is used in modern means of transportation and smart city infrastructures. The mechanical and chemical properties of the selected steel grades in the state of delivery are presented in Table 3.

Table 3. Stale DOCOL composition (own research).

Steel Grade	C%	Si%	Mn%	P%	S%	Al%	Nb%	Ti%
DOCOL 1200 M	0.11	0.21	1.69	0.011	0.002	0.041	0.15	0.024
DOCOL 1300 M	0.14	0.23	1.35	0.012	0.002	0.043	0.16	0.026

The table data show that AHSSs are primarily characterized by a significantly increased Ti content compared with classic structural non-alloy steels. The Ti content in both DOCOL steel grades is more than ten times higher than in C-Mn steels. Analyzing the Schaeffler diagram, it can be seen that Ti is both a ferrito-forming and martensite-forming element, and its action is twice as effective as chromium. Titanium is a chemically active element; it forms various types of non-metallic inclusions, such as TiC, TiO, and TiN, which significantly strengthen the steel but can also initiate junction cracks when the size of these inclusions is too large (above 2 um). At the same time, it can be stated that both tested DOCOL steels have a low sulfur content of 0.002%. A chemical composition selected in this way can obtain good mechanical properties (cf. Table 4).

Table 4. DOCOL 1400M steel and its mechanical properties (own research).

Become	Ys MPA	UTS MPa	Elongation A5, %
DOCOL 1200 M	955	1210	7.3
DOCOL 1300 M	985	1305	6.2

DOCOL 1200 M and DOCOL 1300 M steel sheets with a thickness of 1.8 mm were joined with the MAG (Metal Active Gas) process using two different shielding gases:

- CORGON-10 (EN-439), gas mixture Ar + 10% CO_2;
- CORGON-25 (EN-439), gas mixture Ar + 25% CO_2.

It was assumed that the manufactured joints must be characterized by adequate tensile strength and fatigue strength, as well as adequate plasticity, ensuring their resistance to cracking during operation, e.g., when external factors affect the structures (weather conditions, loads).

Therefore, two electrode wires with different chemical compositions were used for welding: UNION X96 and UNION X90. The recommended chemical composition of both electrode wires is provided in Table 5.

Table 5. Electrode wires—chemical composition of weld metal deposits.

UNION	C%	Si%	Mn%	P%	Cr%	Mo%	Ni%	Ti%
X90	0.10	0.8	1.8	0.010	0.35	0.6	2.3	0.005
X96	0.11	0.8	1.8	0.010	0.45	0.65	2.45	0.007

The differences in the chemical composition of the electrode wires (Table 5) relate mainly to the following:

- Carbon content of titanium and chromium, which affect the strength of the joint;
- molybdenum and nickel, which affect the plastic properties of the joint;

The diameters of the electrode wires were 1.0 mm in each case.
The other MAG welding parameters were as follows:

- Arc voltage, 20.5 V;
- Welding current, 118.5 A;
- DC current source (+) on the electrode.

The tested properties of the thin-walled joint are also influenced by the linear energy of the welding process. In addition to current and voltage parameters, it was necessary to choose the right speed for the welding process. Weld properties were tested for samples measuring 1.8 mm × 200 mm × 340 mm, obtained at the following welding speeds: 260 mm/min and 360 mm/min. In none of the cases was preheating used. The prepared test joints were welded single-walled.

5. Test Methods

After the execution of welded joints for a thin-walled construction, tests were carried out to assess the quality of the joint. Non-destructive testing and destructive testing were performed.

Non-destructive testing (NDT) included

- Visual examination (VT) according to the requirements of PN-EN ISO 17638 and assessment criteria according to EN ISO 5817;
- Magnetic particle testing (MT) according to PN-EN ISO 17638; the test assessment was made according to EN ISO 5817 using a device for testing magnetic flaws: detector type REM—230.

On the other hand, destructive tests included

- A tensile strength test (average of 3 measurements; tests were performed using the INSTRON 3369 testing machine—PN-EN ISO 4136:2013-05);
- A bending test. The parameters of the bending test were as follows: sample width b = 22 mm; sample thickness = 1.8 mm; mandrel d = 15 mm; bending angle = 180°. Five measurements were made in the bending test (number of samples) for each sample from the ridge side and the face side using the INSTRON 3369 testing machine—PN-EN ISO 5173:2010;
- A fatigue strength check using an 8874 INSTRON testing machine with an axial force range of ±25 kN and a torque of ±225 Nm; samples for fatigue test measurements were prepared according with [61] and Figure 1.

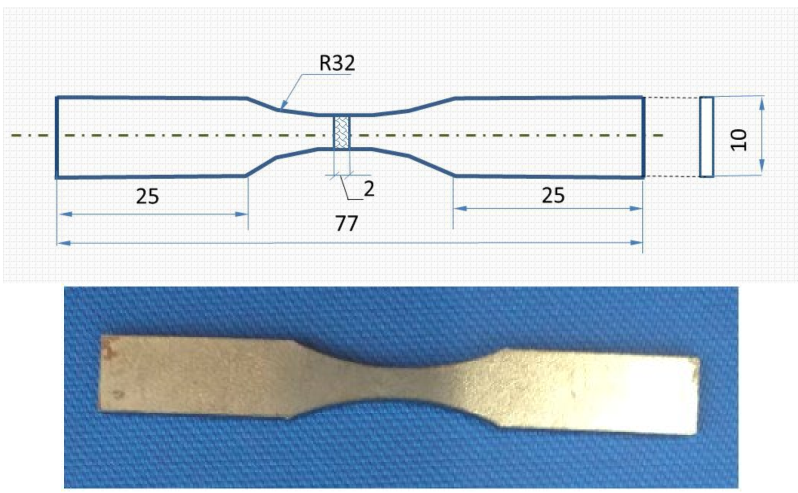


Figure 1. Sample for fatigue test measurements and view of the sample (own research).

The fatigue test was carried out using a cyclical, sinusoidal stress signal. The following parameters of the control signal were used in the fatigue test:

(a) Cycle asymmetry coefficient R = 0;
(b) Stress amplitude = 250 MPa;
(c) Mean value of stress = 250 MPa;
(d) Minimum stress value = 0 MPa;
(e) Maximum stress value = 500 MPa;
(f) Frequency 5 Hz.

After each type of test, samples were selected, and only those that did not show welding defects and inconsistencies were qualified for further stages.

6. Research Results and Their Analysis

The results of the non-destructive tests of the connections are presented in Tables 6 and 7.

Table 6. NDT test results for connectors made of DOCOL 1200 M steel.

Sample	Welding Speed, mm/min	Electrode Wire	Gas	Observed Result
B1	260	Union X90	Ar-10% CO_2	Cracks
B2	360	Union X90	Ar-10% CO_2	No defects
B3	260	Union X96	Ar-10% CO_2	Cracks
B4	360	Union X96	Ar-10% CO_2	No defects
B5	260	Union X90	Ar-25% CO_2	Cracks
B6	360	Union X90	Ar-25% CO_2	No defects
B7	260	Union X96	Ar-25% CO_2	Cracks
B8	360	Union X96	Ar-25% CO_2	No defects

Table 7. NDT test results for connectors made of DOCOL steel 1300 M.

Sample	Welding Speed, mm/min	Electrode Wire	Gas	Observed Result
B9	260	Union X90	Ar-10% CO_2	Cracks
B10	360	Union X90	Ar-10% CO_2	No defects
B11	260	Union X96	Ar-10% CO_2	Cracks
B12	360	Union X96	Ar-10% CO_2	No defects
B13	260	Union X90	Ar-25% CO_2	Cracks
B14	360	Union X90	Ar-25% CO_2	No defects
B15	260	Union X96	Ar-25% CO_2	Cracks
B16	360	Union X96	Ar-25% CO_2	No defects

The results of the NDT tests presented in Tables 5 and 6 indicate that welding parameters have a significant impact on the quality of the joint. Poorly selected welding parameters caused the formation of small cracks (maximum three) in joints about 2–3 mm long. Cracks were more frequent in the HAZ (heat-affected zone) than in the weld. Such connections could not be used on selected elements of smart city infrastructure or in electric vehicles, as they would not meet the basic assumptions regarding operational safety. An analysis of the literature [60,61] indicates that the most common cause of cracks in the new AHSSs studied is their dominant martensitic structure, the presence of overgrown, non-metallic inclusions, and too-high linear energy in the welding. This is also confirmed by the research results. The table data show better results were achieved using a higher welding speed (360 mm/min) and, therefore, when welding with lower linear energy. At this research stage, no influence of electrode wire selection on the correctness of the welded joints was noted. For further examination, only those samples that did not show welding defects and incompatibilities (B2, B4, B6, B8, B10, B12, B14, B16) were taken.

After assessing the joints with NDT tests, a tensile strength test was performed. Appropriately high plastic properties in the joints determined the operational suitability of the welded structures. According to data from the literature [63] and standards, welded structures for selected applications should have a tensile strength of at least 500 MPa. The strength of the connections was tested using the INSTRON 3369 testing machine. The results of the endurance tests (an average of three trials) are presented in Table 8.

Table 8. Tensile strength test (UTS) results of welded joints made of DOCOL 1200 M and DOCOL 1300 M steel.

Sample No.	UTS, MPa	A5
B2	684	6.4
B4	702	6.4
B6	678	6.5
B8	669	6.5
B10	755	6.1
B12	760	6.1
B14	763	6.1
B16	745	6.2

The results indicate that all joints are characterized by sufficiently high tensile strength. The table data show that higher tensile strength in the joints was obtained when DOCOL 1300 M steel, characterized by higher C and Ti content compared with DOCOL 1200 M steel, was used. The results of the tests also indicate that higher strength was obtained using UNION X96 electrode wire with increased C and Ti content compared with UNION X 90 wire. The result is in line with the adopted assumptions. A beneficial effect of using an argon gas mixture with lower CO_2 content on the higher strength of the joint was also noted.

Then, a bending test on the joints was carried out for selected DOCOL 1200 M and DOCOL1300 M steel samples. For sample B4 (highest strength for a joint made of DOCOL 1200 M steel) and for sample B14 (highest strength for a joint made of DOCOL 1300 M steel), five measurements were made in the bending test for each sample from the ridge side and the face side. After testing, no cracks were found in either the weld or the SWC. The evaluation of the studies is positive (Figure 2).

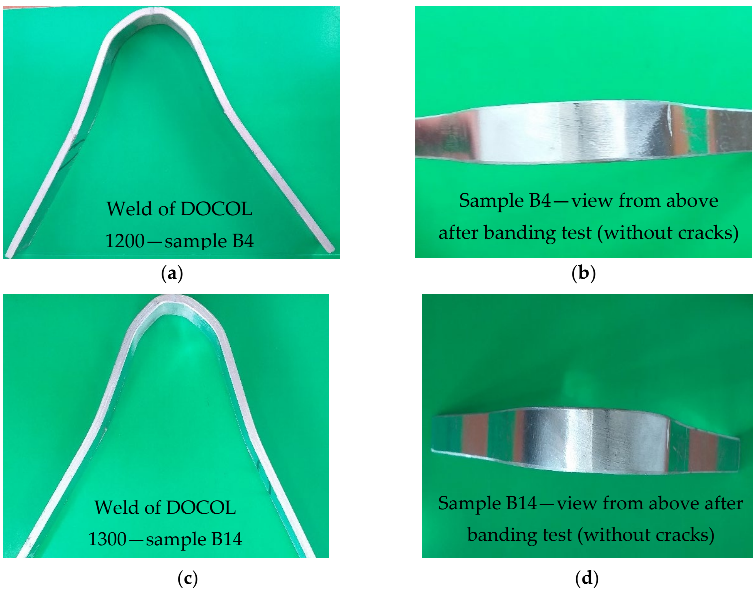
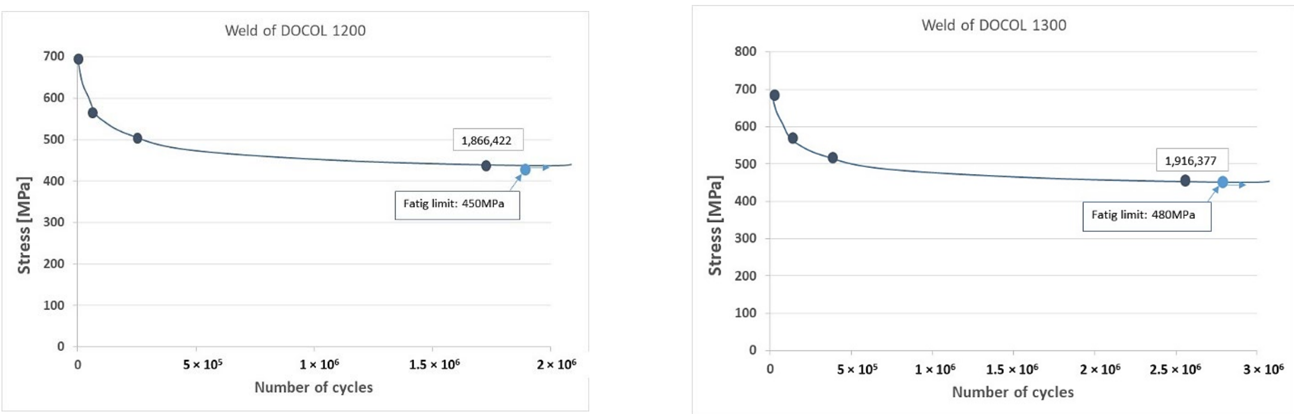


Figure 2. Samples after banding tests: (**a**,**b**) weld of DOCOL 1200; (**c**,**d**) weld of DOCOL 1300.

To confirm the suitability of the selected materials for applications for selected light welded structures in smart cities, fatigue tests had to be carried out, proving the service life of the tested joints.

For this purpose, the fatigue strength value for samples B4 and B14 was checked (Figure 3). The fatigue test was performed using an 8874 INSTRON testing machine with an axial force range of ±25 kN and a torque of ±225 Nm. A fatigue limit was determined for both test samples. The fatigue test for sample B4 (DOCOL steel junction 1200 M), with an applied stress value of 440 MPa, showed a crack occurrence after a number of load cycles—1,866,422. This is the expected value for the fatigue limit of the joint for 2 million cycles. Based on this result, it can be concluded that with a stress value slightly below 440 MPa, the material will have infinite fatigue life. A similar test was performed for a sample made of DOCOL 1300 M steel. A fatigue test for sample B14, with a stress value of 480 MPa applied, showed the occurrence of a crack after 1,916,377 load cycles. This is a positive expected value for the coupling fatigue limit for 2 million cycles. Based on this result, it can be concluded that, with a stress value slightly below 480 MPa, the material will have infinite fatigue life. Positive effects of fatigue strength tests show that thin-walled welded structures made of these steels will meet high operational safety conditions and constitute a peculiar material for applications involving the selected thin-walled welded structures in smart cities.



(**a**) (**b**)

Figure 3. Fatigue test results: (**a**) weld of DOCOL 1200; (**b**) weld of DOCOL 1300.

To sum up, it should be stated that the test results indicate that the biggest disadvantage of the obtained connections is the inability to obtain similar strength properties in the joint in relation to the base material in the MAG welding process.

The introduction of changes in the technology related to joining the tested materials could result in better strength parameters in the joint and new possibilities for their applications. The weldability results for the DOCOL steels suggest that it could become an important material not only in the creation of a smart city but also an important construction material in the automotive industry. Such suggestions have been taken up by all the authors of this article in previous joint papers. High fatigue strength and good fatigue properties together with the controlled possibility of welding make it possible to use a safe, thin-walled, much lighter structure for the construction of mobile platforms, bus frames, and passenger car bodies. This could be a very real solution in creating modern electric buses and other means of transportation for smart cities. For example, electric means of transportation should be as light as possible, but in reducing the weight, they must not lose their mechanical properties. Lighter vehicles will translate into lower fuel consumption and less traffic noise. The authors of essential articles on technology and smart cities also came to similar conclusions [64–68].

7. Summary

The smart city concept is constantly being developed, and the developed solutions are subject to evaluation and improvement [69,70]. The directions of the development of smart cities strive to improve the quality of life in all research areas, i.e., smart buildings, smart environments, intelligent energy, smart transportation, and intelligent IT communication. Research conducted in these areas is related to sustainable development and the safety of people and things. A dynamically developing research trend is research on new materials and technologies that offer an increasingly wide possibility of applications for the production of smart products. Research on smart materials and technologies is definitely leading to this area. Testing other construction materials, including structural steels with increased strength properties, is a research niche. This article presents research on the AHSS material group intended for applications in smart cities, e.g., in transportation engineering for elements of electric vehicles; load-bearing structures for point infrastructure, such as shelters and stops; and aspects of construction structures. At the present stage of research, it can be emphasized that satisfactory results in strength tests have been achieved, emphasizing the possibility of using welded structures made of new steels for the proposed applications. It was demonstrated that it is possible to make a thin-walled joint with a thickness of 1.8 mm and with a tensile strength above 700 MPa. The results of the tests confirmed that connectors made of DOCOL 1300M steel have a higher tensile strength than connectors made of DOCOL 1200 M steel. In addition, it has been shown that

- The electrode wire for welding both DOCOL steels should contain higher C and Ti contents;
- The argon-shielding gas mixture should contain a CO_2 addition of 10%, although a 25% mixture is more commonly used in welding.

To check the passive safety of future welded structures made of new steel materials, bending tests and fatigue strength tests were carried out. Positive results were achieved, as no cracks were found in the bending test on the side of the ridge or the side of the weld face, and the fatigue strength in both cases significantly exceeded the value of 400 MPa.

The positive results of all the tests allow us to recommend connectors from both new DOCOL steel grades we tested for safe, responsibly selected constructions for smart city purposes. Not all application possibilities for DOCOL steel have been fully discovered. The research results presented in this manuscript may be helpful information for future studies in the field of smart cities. The proposed solutions will allow for a significant slimming of the structure while maintaining its high strength requirements, so the authors suggest that the solutions, in the future, will translate into the following:

- The reduction of energy consumption in mobile vehicles;
- In the case of load-bearing bus structures made of light, more durable structures, the passive safety of the vehicle will be increased, and this will enable the transportation of more people as the load capacity of the vehicle will be increased.

Smart city planning must be comprehensive and urgently changed; it cannot be limited only to new solutions in the field of information transfer and data analysis. In order for future structures to be improved and able to cooperate with new technological solutions, it is also necessary to focus on construction materials. This article supports the implementation of new material solutions in smart city transportation engineering; the presented research results may be helpful information for future research and the use of construction materials in urban transport systems.

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Data Availability Statement: According to our university's Ethical Statement, the following shall be regarded as research requiring a favorable opinion from the Ethics Commission in the case of human research (based on a document in Polish: https://prawo.polsl.pl/Lists/Monitor/Attachments/7291/M.2021.501.Z.107.pdf (accessed on 21 March 2022)): Research in which persons with limited capacity to provide informed consent; research on persons who do not have the capacity to give informed or free consent to participate in research and who have a limited ability to refuse research before or during their implementation (in particular, children and adolescents under 12 years of age and persons with intellectual disabilities), persons whose consent to participate in the research may not be fully voluntary, including prisoners, soldiers, police officers, employees of companies (when the survey is conducted at their workplace), and persons who agree to participate in the research on the basis of false information about the purpose and course of the research (masking instructions, i.e., deception) or do not know at all that they are subjects (in so-called natural experiments); research in which persons particularly susceptible to psychological trauma and mental health disorders are to participate mental health research, in particular, mentally ill persons, victims of disasters, war trauma, etc.; patients receiving treatment for psychotic disorders; family members of terminally or chronically ill patients; research involving active interference with human behavior aimed at changing it; research involving active intervention in human behavior aimed at changing that behavior without direct intervention in the functioning of the brain, e.g., cognitive training, psychotherapy psychocorrection, etc. (this also applies when the intended intervention is to benefit the subject (e.g., to improve his/her memory)); research concerning controversial issues (e.g., abortion, in vitro fertilization, the death penalty) or requiring particular delicacy and caution (e.g., concerning religious beliefs or attitudes toward minority groups); research that is prolonged, tiring, or physically or mentally exhausting. Our research was not performed on people meeting the mentioned conditions. None of the researched people had a limited capacity to be informed or were susceptible to psychological trauma and mental health disorders; the research did not concern the above-mentioned controversial issues; the research was not prolonged, tiring, or physically or mentally exhausting.

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