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НАУЧНАЯ СТАТЬЯ
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DEFINING WORKING PARAMETERS OF CONVEYOR-TYPE PIPE FEEDING SYSTEMS FOR TRENCHLESS PIPELINE INSTALLATION AND MINING

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Abstract: Analyzing the lab and job site testing data related to friction and clamping interaction between rubber compound-lined track-type conveyors and steel pipes in pipe feeding systems used in trenchless construction the article gives insight into major engineering principles behind the distribution of forces and reactions inside conveyor-based pipe feeding systems with axial force over 200 tons and discloses the relation between the parameters of the pipe and working characteristics of the continuous pipe feeding system. The research allowed to define the necessary clamping force developed by a 200-ton machine, maximum achievable friction factor consistent with the strength of steel rubber-coated conveyor plates and the ability of the most popular pipes used in trenchless industry to withstand the radial loads communicated by rubber-coated pads of the pipe feeder.

Keywords: friction and clamping interaction, rubber compound-lined track-type conveyors, pipe feeding systems, clamping force, friction factor, trenchless industry

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ОПРЕДЕЛЕНИЕ РАБОЧИХ ПАРАМЕТРОВ КОНВЕЙЕРНЫХ СИСТЕМ ПОДАЧИ ТРУБ ДЛЯ БЕСТРАНШЕЙНОГО ТРУБОПРОВОДНОГО СТРОИТЕЛЬСТВА И СКВАЖИННОЙ ДОБЫЧИ ПОЛЕЗНЫХ ИСКОПАЕМЫХ

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Аннотация: Приведены результаты лабораторных испытаний и полевого тестирования гусеничных конвейеров с обрезиненными металлическими пластинами для непрерывной осевой подачи стальных труб конвейерного типа, используемых в бестраншейном строительстве. Выполненные исследования дают представление об основных инженерных принципах, лежащих в основе распределения усилий и реакций внутри конвейерных систем подачи труб с осевым усилием более 200 тонн, а также раскрывают взаимосвязь между параметрами трубы и рабочими характеристиками системы непрерывной подачи труб. Исследования позволили определить: необходимое радиальное усилие, создаваемое 200-тонной машиной; максимально достижимый коэффициент трения, соответствующий прочности стальных конвейерных плит с резиновым покрытием; способность наиболее популярных труб, используемых в бестраншейной промышленности, выдерживать радиальные нагрузки, передаваемые обрезиненными пластинами толкателя труб.

Ключевые слова: трение и радиальные усилия, гусеничный конвейер с обрезиненными металлическими пластинами, системы осевой подачи труб, радиальное усилие, коэффициент трения, бестраншейная технология прокладки труб

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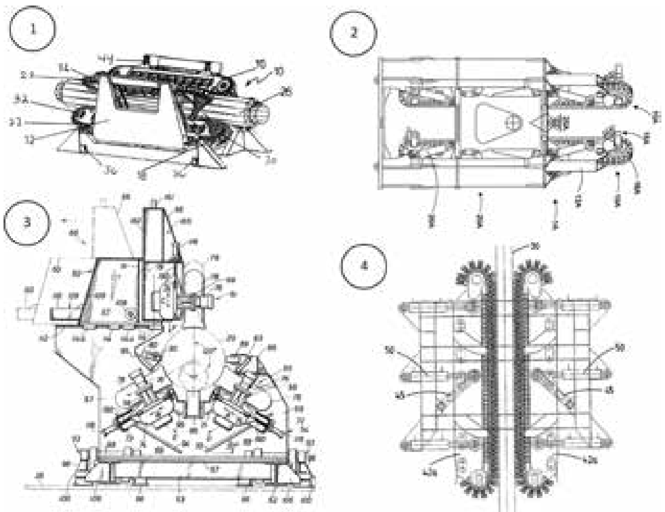
Introduction

Over the course of their long history drilling, mining and pipeline industries set multiple objectives related to the design of devices for axial translocation of pipes and cables. Various companies have solved these problems in different ways and the existence of a large number of modifications of these devices and patents for their design, as well as related technologies, prove the importance of finding the answer to the question of the most optimal design of a pipe pusher and its maximum operating parameters.

Materials and Methods

On the 21st of October 1970 J. Ray McDermott & Co., Inc, New Orleans, LA filed a patent for a PIPE TENSIONING APPARATUS [1] (pipe feeder), which had a series of independently driven traction wheels located radially around the pipeline. Such pipe tensioning devices have been used in line to feed pipelines and cables from pipeline ship decks to the sea bottom along with other types of pipe feeding systems. See picture 1.

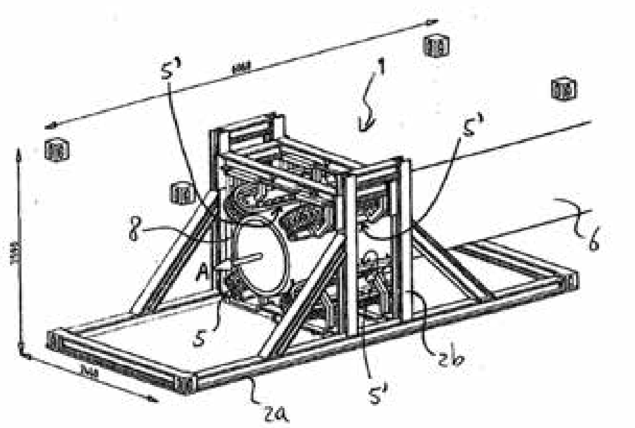


Picture 1. Pipe tensioners (sometimes referred to as pipe feeders):1-Invented by Ottmar Diehl in 2006; 2-Invented by Andrew Harrop, Ludovic Lacan, Martin Pierre, Paul McMillan in 2018, 3- Invented by Edwin J. Dressel, Warren A. Petrie, Clarence W. Shaw, Janis Grinbergs, John Isakson, Martin Adams in 1972; 4- Invented by Joop Roodenburg, Terence Willem August, Wehmeijer, Den Haag in 2011
Рисунок 1. Устройства для натяжения труб (иногда называемые устройствами подачи труб): 1 - Изобретено Оттмаром Дилем в 2006 году; 2 - Изобретено Эндрю Харропом, Людовиком Лаканом, Мартином Пьером, Полом Макмилланом в 2018 году; 3 - Изобретено Эдвином Дж. Дресселом, Уорреном А. Петри, Кларенсом У. Шоу, Янис Гринбергс, Джон Исаксон, Мартин Адамс в 1972 году; 4 - Изобретено Йоопом Руденбургом, Теренсом Виллемом Августом, Вехмейером, Ден Хаагом в 2011 году

Similar patents for pipe tensioning devices were filed between 2005 and 2018 [2-4]. These pipe tensioners or pipe feeders for marine industry and horizontal directional operations were built with tracks, not wheels. The most popular conveyor-based pipe feeders, which were built for horizontal directional drilling by the Dutch company Van Leeuwen [5] are capable of the maximum axial thrust of 130 tons even for pipelines of large diameters: see Picture 2.

If a pipe feeder should be used in HDD, it should be commensurate with the thrust force of an HDD rig [6]. The necessary thrust force of a horizontal directional drilling rig used for construction depends on the diameter and wall thickness of the pipeline, length of the crossing, drilling trajectory and geological conditions in the formation [7,8].

The most popular drilling rigs used for HDD trunk pipeline crossings range between 150 and 400 tons. The cylinder driven pipe pushing devices (Pipe Thruster by Herrenknecht, Pipe Pusher by Prime Drilling and MTS) used to communicate additional axial force in pipe pulling operations and emergency situations when the steel pipe gets stuck in the drill hole and needs to be salvaged by pulling out of the hole from the pipe side range between 300 and 750 tons (see picture 3). In extremely complicated projects two 750-ton pipe thrusters are used in line with each other to pull or push one pipeline with the combined axial force of 1500 tons. The most cylinder driven pipe pushers have been effective, but they are heavy, require extremely complicated foundations, cannot feed the pipeline continuously stopping the clamping unit to reverse it every 3-4 meters of the pipe. Every time the pipeline stops, it is necessary to overcome static friction and the thrust force diagram shows peak values every time the pipe starts moving whereas conveyor-based pipe feeding systems do not need to waste time on reverse motion and require less thrust reserve offering better control of the face pressure.



Picture 2. Pipeline pressure device with endless conveyor members for use during a horizontal directional drilling process by Gebr. Van Leeuwen Harmelen B.V. (published in 2010)
Рисунок 2. Толкатель трубопровода с бесконечными конвейерными элементами для использования в процессе горизонтально-направленного бурения, разработанное компанией Ван Левен Хармелен Б.В. (опубликовано в 2010 году)

Picture 3. Cylinder based pipe thruster produced by the German company Herrenknecht since 2006
Рисунок 3. Доталкиватель труб с цилиндрами, выпускаемый немецкой компанией Herrenknecht с 2006 года

Due to relatively small thrust force of conveyor-based pipe feeders they are rarely used in big pipeline operations, as it is necessary to use too many small pipe feeders to match at least a 500 ton pipe pusher of the cylinder type [9]. Hence, it is necessary to increase the possible thrust force of single conveyor-based pipe feeder to use two 250 ton pipe feeders instead of 4 smaller units.

The difficulty of designing and building a 200 or 250 ton conveyor-based pipe feeder resides in the necessity to achieve a formidable clamping force for maximum friction between the pads of the pipe feeder and the surface of the pipe. It is clear that the necessary compression for achieving thrust beyond 250 tons will break some of standard steel and plastic pipes and the device will not be universal for all pipes. But it is possible to build a machine with adjustable clamping force [10,11]. Hence, it is expedient to conduct research activities in the direction of the achievable friction and maximum clamping pressure on the pipe [8,12].

In 2024 Universal HDD built a 200 ton continuous pipe feeder capable of intermittent 250 tons at maximum hydraulic pressure [13] See picture 4. The patent was granted to Vasily Anishchenko in 2022.

Proceeding from the necessity to keep balance between friction and clamping force, it is necessary to analyze how continuous conveyor-based pipe feeding machines interact with pipelines at maximum loads. A pipe feeder should not compress pipes to exceed the yield point of their steel. To calculate the most effective radial force of the pipe feeder and in order to follow the conditions of the above mentioned balance, it is expedient to calculate the applicable clamping pressure and prove the applied calculation methods by communicating maximum clamping pressure to various pipes. Proceeding from permissible clamping pressure and friction factor measured in the lab for various types of pads, it can be possible to determine the maximum achievable thrust force. The primary objectives of the research should be set as follows:

1. Calculate critical radial forces related to various pipeline diameters and wall thickness, which can be pushed by a conveyor-type continuous pipe feeder with tracks of a certain length and a particular rubber-covered pad area for clamping the pipeline to achieve an axial force of 200 tons or more;

Picture 4. Pipe feeding device built by Universal HDD in 2024
Рисунок 4. Устройство для подачи труб, построенное компанией Universal HDD в 2024 году

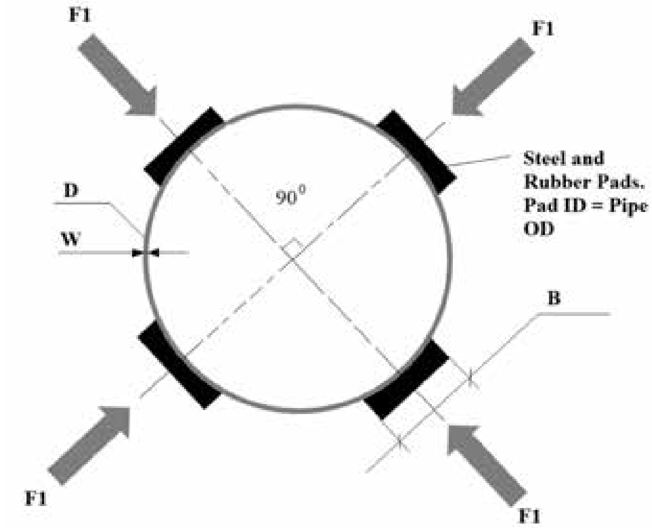
2. Define if the theoretically calculated clamping forces are commensurate with achievable friction forces between the conveyors and the pipe on a special lab stand;

3. Run practical tests on real pipes applying maximum clamping pressure on the pipe installed inside a conveyor-type pipe feeding system.

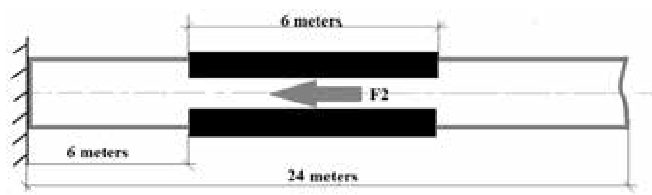
As the cylinder type 750 ton Pipe Pushers have been in use since 2005, the necessity to analyze critical forces for buckling and longitudinal compression of pipelines is not relevant. Axial pipe pushing technology proved its effectiveness over the years of use, but the compression of various pipelines by 4 track conveyors has not been analyzed yet.

It important to define the theoretical compression force applicable to various pipelines before experimenting with friction of pads on the pipe.

Pictures 5 and 6 describe the load schematics for the pipeline compressed between 4 conveyors. The pipeline is pressed between four sets of pads, which, communicate axial load simultaneously with the radial load. The pipeline is not filled with any gas or liquid, so it does not have any pressure inside. Hence, we can calculate the critical clamping force using finite element analysis.



Picture 5. X-sectional view of the pipe and pressing pads: ermissible pressing force (F1); diameter (D); wall thickness (W) of the pipeline of certain steel and the width of the pads (B)
Рисунок 5. Поперечный разрез трубы с приложенной радиальной нагрузкой: опустимое усилие прижатия (F1), диаметр (D), толщина стенки (W) трубопровода из определенной стали и ширина прижимных пластин (B)



Picture 6. Side view of the pipe / *Рисунок 6.* Вид трубы сбоку

Results

In order to calculate the critical clamping force for a pipeline using finite element analysis, let us assume that the pipeline has in infinite length. In this case fixing the ends of the pipe is of no importance [14,15]. The elongations and shifts in the pipe in this case should not be considered. It means that every section of the pipe in the region of the applied force is deformed in identical patterns. Thus, the critical pressure for the pipe can be defined from the equation bellow:

$$q_n = \frac{(n^2-1)EI}{R^3} \; [12] \tag{1}$$

Taking into consideration that the fundamental functions for this critical load would be v=sinφ; w=-ncosφ,
where *n*- number of radial waves;
E – steel elasticity module;
I – moment of inertia of the ring;
R – ring radius.

As the pipe is not a ring and it is bent along its length due to buckling, the critical force for a pipe can be calculated from the following equation [14,15]:

$$q_n = \frac{DR\left[\left(\frac{m\pi}{l}\right)^2+\left(\frac{n}{R}\right)^2\right]}{n^2} - \frac{Eh\left(\frac{m\pi}{l}\right)^4}{n^2\left[\left(\frac{m\pi}{l}\right)^2+\left(\frac{n}{R}\right)^2\right]^3}, \tag{2}$$

where *m* - the number of longitudinal waves (in this case m is stipulated by the number of conveyors around the pipe);
l - the length of the conveyor in contact with the pipe.

The results of theoretical calculations of critical clamping force for pipes of various diameters and wall thickness for two different steel types taking both compression and bucking into consideration are set forth in table 1:

Table 1 / Таблица 1

Steel Pipeline Compression Analysis / Анализ трубопроводов на сжатие

Pipe Dia	Pipe Wall	12" Pad	14" Pad	16" Pad	22" Pad
		Critical Force	Critical Force	Critical Force	Critical Force
Critical Force = force required (Tons) to induce Yield Stresses Based on x80, Sy=80,496 psi					
20"	0.276"	453	1,500	NA	NA
20»	0.787"	2,195	3,352	NA	NA
28»	0.354"	319	227	261	NA
28»	0.827"	1,011	1,156	1,329	NA
32»	0.354"	171	306	203	2,202
32»	0.827"	810	927	1,056	5,152
40»	0.394"	208	151	240	529
40»	0.827"	624	663	722	1,149
48»	0.472"	379	281	171	343
48»	0.827"	493	522	595	756
56»	0.630"	263	442	390	367
56»	0.827"	407	527	520	557
Critical Force = force required (Tons) to induce Yield Stresses Based on x100, Sy=94,275 psi					
20"	0.276"	531	1,757	NA	NA
20»	0.787"	2,571	3,926	NA	NA
28»	0.354"	374	266	306	NA
28»	0.827"	1,184	1,354	1,557	NA
32»	0.354"	200	359	237	2,579
32»	0.827"	949	1,085	1,237	6,034
40»	0.394"	244	177	282	620
40»	0.827"	731	776	845	1,346
48»	0.472"	444	330	201	401
48»	0.827"	577	611	697	886
56»	0.630"	308	518	457	430
56»	0.827"	477	617	609	653

It should be noted that only two diameters were used for convex surfaces to have only two types of pads for all applicable diameters.

The designed pipe feeder is equipped with 16X6 inch cylinders. The cylinders are of equal length and hold the conveyors at 45 degrees to vertical and horizontal axes. The calculation for F1 from picture 4 is drawn in table 2. The calculations are based on generally acknowledged principles of hydraulics [16]:

Table 2 / Таблица 2

Calculation of force F1 from picture 5 for 4000 PSI / Расчет силы F1 (см. рисунок 5) с давлением в цилиндрах 4000 фунтов на квадратный дюйм

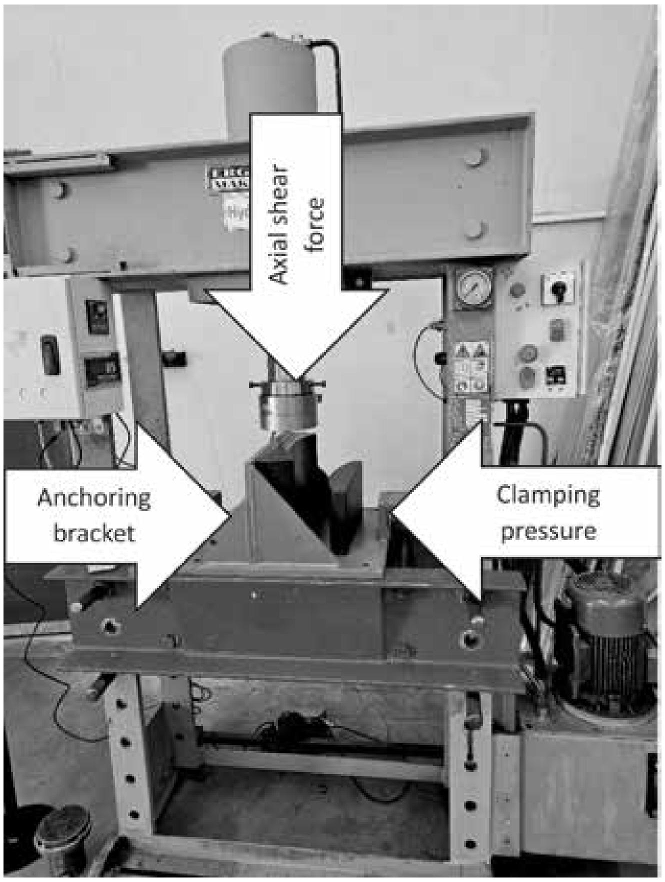
Parameters	Designation	Dimension	Meaning
Bore diameter of the cylinder	D	in	6,00
Pressure inside the cylinder	P	psi	4 000,00
Force developed by one cylinder	F cyl.	lbs	113 040,00
Force developed by 4 cylinders	F 4 cyl.	lbs	452 160,00
Force as indicated in diagram	F1	lbs	339 120,00

The results of the calculation show that not all pipes can be clamped with maximum pressure, but if confirmed in a practical test, the results can be used as a guideline to choose the correct pipeline for adequate necessary axial force. It means that not all pipes can be pushed with maximum pushing force of the pipe feeder. This leaves the question of correct friction factor open. It is indispensable to make sure that the friction factor is sufficient to prevent slipping between the surfaces of the pipe and the pads. In order to calculate the necessary friction factor, it is necessary to use the sum of clamping forces of any two conveyors at 90 degrees to each other projected on one plane. The forces developed by all opposite cylinders should in this case be considered reactional. The sum of clamping forces of two groups of cylinders at 90 degrees to each other projected on a single plane is 904 320 lbs, which is 411 tons. This means that the friction factor considered while engineering the compound for steel-rubber plates for a 200 ton pipe feeder should exceed 0.5 [17]. Hence the technical solution for achieving the maximum friction factor and not damaging the pipe while clamping and pushing at the same time is a certain priority.

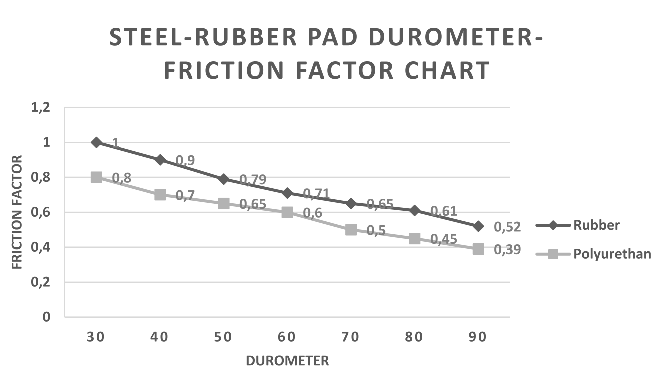
The balance between clamping forces and the necessary friction is essential for the design of any pipe feeding system. The paradox and the key point of the technology is the correlation between the hardness of rubber measured by durometer on the scale from 0 to 100 and the friction factor. The results of lab experiments proved the possibility to achieve the friction factor over one, but in this case the durometer showed figures below 30 on its scale. The rubber or polyurethan compound with this hardness applied to steel base does not hold the shear force necessary for 200 tons axial force. When the rubber compound durometer is raised to 90, the compound proves very strong and holds all loads, but the friction factor is below 0.4. It is impossible to theoretically predict the exact correlation between the properties of the rubber compound and achievable friction in various conditions. So the processes of developing the pipe feeding technology proved it indispensable to stage a lab experiment determining the dependence between the properties of rubber compound and friction. In order to mimic the working conditions of the system, real-size pads were installed into the frame of a hydraulic press with two perpendicular cylinders. One cylinder stood for clamping and the second cylinder worked as a substitution for friction. The simulation of the pipe surface was represented by a semi-circular polished steel plate. The laboratory test stand is shown in picture 7.

The test had to show which materials could be used for the pads and which friction factors can be developed as a result of experiment. It is understandable that polyurethane is more durable than rubber when it comes to compression, it is cheaper than rubber, and considering the formidable clamping force developed by the pipe feeder it certainly looked like the most preferrable material for the high-power pipe feeding system. On the other hand, its friction factor on steel and plastic surfaces can be lower. Picture 8 shows the results of measuring the friction factor between the surface of the pipe and various types of polyurethan and rubber.

It should be noted that the experiment showed that all rubber pads with durometer below 70 and all polyurethan pads with durometer below 60 failed to hold the shear load of 200 tons divided by the number of pads in contact with the pipe at any moment of time. It means that only pads with durometer 70 for polyurethane and 80 for rubber. The test results show that the friction factor with polyurethane pads is in conflict with the friction factor requirements set forth above. Hence only rubber pads can be considered with compounds of durometer 80 and 90. As the rubber compound with durometer 80 holds the shear load and offers the highest friction factor, it should be considered the best match for the pipe feeder structure despite its high price.



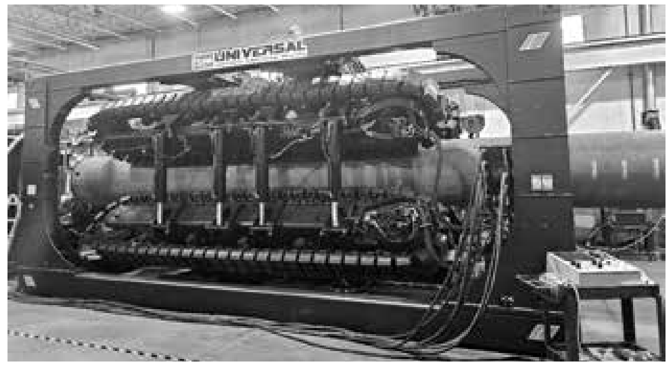
Picture 7. Test stand for measuring the strength of rubber pads and friction factors
Рисунок 7. Испытательный стенд для измерения прочности обрезиненных прижимных пластин и коэффициента трения



Picture 8. Durometer-Friction factor dependence for rubber and polyurethan
Рисунок 8. Зависимости коэффициента трения от твердости для резины и полиуретана

Discussion

All results of calculations and lab tests can only be considered trustworthy if proven by maximum load tests on actually produced machines. The results of pad clamping-shear tests can be trustworthy for a single pad, whereas the critical clamping forces should be tested on real pipes. The design of the first Universal HDD pipe feeder was based on theory and results of lab tests, but after it was assembled, two pipes were purchased and subjected to maximum load test at 5000 psi for the duration of 5 minutes. Picture 9 shows the pipe feeder at maximum load at 5000 psi with a 40 inch pipeline with 0.827” wall thickness. The pipe held the load the rubber-coated pads remained intact, which proved the correctness of all theoretical calculations and confirmed the chosen approach to structural analysis of the machine.



Picture 9. Pipe feeder of Universal HDD at factory tests in the shop at Lake Zurich, IL
Рисунок *9.* Устройство подачи труб универсального жесткого диска на заводских испытаниях в цехе на озере Цюрих, Иллинойс

Conclusion

In conclusion it should be noted that both the structure of the pipe feeder and the pipe could hold the calculated critical force, it proved possible to develop the pipe feeding device and apply to most popular steel pipes the formidable clamping force necessary to develop the axial thrust exceeding 200 tons, which is confirmed by tests on pipes clamped in an actual 200 ton pipe feeding machine. The balance between friction and clamping force can be achieved with rubber-steel pads with rubber durometer 80 and friction factor 0.6. This research proves that it is possible to use conveyor type pipe feeding machines along with cylinder-based and rack and pinion pipe pushing devices for the construction of trenchless crossings under natural and artificial obstacles like rivers, hills, roads and railroads [18,7,19]. Several pipe feeding systems can be used along one pipeline in pipeline installations for trenchless and marine industry, the new equipment can be used for drilling evacuation galleries in mining or for mining ores from large diameter drill holes. The use of such powerful machines with micro tunneling equipment helps operators to keep continuous pressure on the face and increase tunneling speed.

The main advantage of such systems is their light weight and the absence of the need to build massive foundations, the technology allows the use of standard anchor solutions for HDD machines. There is no need for a crane during the installation of a pipe feeder with tracked conveyors, while a 150-ton crane is necessary to install a cylinder-driven pusher and one clamping unit of this machine without the main jacking cylinder weighs as an entire conveyor-type pipe feeder. Therefore, the design and production of a powerful continuous pipe feeder is a promising direction of technological development in the mining industry.

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